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EDITED BY

THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY

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EDITED BY

THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY

With the Active Collaboration of

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THE

JOURNAL OF GEOLOGY

JANUARY-FEBRUARY 1917

SYMPOSIUM ON THE AGE AND RELATIONS OF THE FOSSIL HUMAN REMAINS FOUND AT VERO, FLORIDA

Dr. E. H. Sellards, State Geologist of Florida

Dr. Rollin T. Chamberlin, Geologist, University of Chicago

Dr. T. Wayland Vaughan, Geologist in Charge of the Coastal Plain Investigations of the United States Geological Survey

Dr. A. Hrdlička, Curator of Physical Anthropology, United States National Museum

Dr. O. P. Hay, Research Associate, Carnegie Institution of Washington

Dr. G. G. MacCurdy, Anthropologist, Yale University

Editorial Note.—In the issue of the *American Journal of Science* of July, 1916, Dr. E. H. Sellards, state geologist of Florida, announced the discovery of fossil human bones and artifacts in association with the relics of many extinct vertebrates in a stream deposit near Vero on the east coast of Florida. In the issue of *Science* of October 27, 1916, there appeared a supplementary article, by the same author, giving additional data bearing on the age and relations of these interesting remains. About the same date there appeared a more comprehensive statement in the *Eighth Annual Report of the Florida Geological Survey.* Soon after the issuance of the first paper, Dr. Sellards submitted to the editors of the *Journal of Geology* an additional article emphasizing certain aspects of the question of man's relationship to the

extinct vertebrates not set forth with equal fulness in the previous article. The tender of this manuscript was accompanied by a very cordial invitation to visit the deposits at Vero and make independent examination. Similar invitations were extended to representatives of the Smithsonian Institution, the National Geological Survey, and other institutions and individuals interested in the subject. This opportunity for co-operative inspection before publication fell happily into the policy of the *Journal*, especially as the crowded state of its columns did not permit immediate publication. While the *Journal of Geology* does not hold itself immediately responsible for the conclusions advanced by its contributors, it desires, so far as possible, when the issues are vital, that all tenable aspects of interpretation shall be placed before its readers that they may form their own conclusions on the amplest available basis.

A conference was finally arranged for the last of October, in which there participated Dr. A. Hrdlička, anthropologist of the United States National Museum; Dr. T. Wayland Vaughan, geologist in charge of the coastal plain investigations of the United States Geological Survey; Dr. O. P. Hay, special student of Pleistocene vertebrates; Dr. G. G. MacCurdy, anthropologist of Yale University; and Dr. R. T. Chamberlin, as representative of the *Journal of Geology*. The members of the conference enjoyed the guidance and assistance of Dr. Sellards; his assistant, Mr. H. Gunter; and his local colleagues, Mr. Isaac M. Weills and Mr. Frank Ayers, whose courtesies were unbounded. The visits of these special students were only partially concurrent, that of Dr. Chamberlin extending from October 23 to 28, that of Dr. Hrdlička from October 25 to 30, that of Dr. Hay from October 25 to 31, that of Dr. MacCurdy from October 25 to 29, and that of Dr. Vaughan from October 27 to 30; hence, while all met upon the ground, their examinations were largely independent. The present assemblage of the several statements of these visiting investigators into a symposium, in connection with the paper of Dr. Sellards—revised after the conference—was arranged without specific knowledge of the conclusions of any of the visiting parties, except, of course, those of the *Journal's* own representative, and the independence

of the reports has been preserved in passing the manuscripts through the press. The statements are arranged in the order of their receipt.

The dates of issuance of this and the preceding number of the *Journal* have been advanced, so that this important assemblage of data might be in the hands of those specially interested before the holiday meetings of the scientific societies, while, at the same time, delay in publishing other waiting articles might be avoided.—Editors.

ON THE ASSOCIATION OF HUMAN REMAINS AND EXTINCT VERTEBRATES AT VERO, FLORIDA

E. H. SELLARDS
State Geologist of Florida, Tallahassee, Florida

CONTENTS

The presence of vertebrate fossils in deposits exposed near Vero in eastern Florida first became known in 1913. Fossil human remains were not found at this locality, however, until October, 1915. Subsequently additional human skeletal material was obtained in February, April, and June, 1916. The associated fossils, which are numerous and varied, have been collected practically continuously since the locality became known, although the largest collections are those made in February, 1915, and in February, April, June, October, and November, 1916. During the latter part of October the writer and his associates in Florida enjoyed and profited by the presence at this locality of Drs. Hay, MacCurdy, Hrdlička, Vaughan, and Chamberlin, all of whom are participants in the present discussion. The writer is also personally indebted to the several specialists in different branches of paleontology who have identified and described fossils from this locality, acknowledgment of which is made in the subsequent pages of this paper.

The discovery of human remains in association with extinct vertebrates at this locality was announced by the writer in the

issue of the *American Journal of Science* of July, 1916. Later discoveries were described in *Science* in the issue of October 27, 1916. Subsequently, in the *Eighth Annual Report of the Florida Geological Survey*, published in October, 1916, the human remains and the associated fossils were more fully described. The present paper includes supplementary observations made during October and November, 1916.

SKETCH MAP OF THE LOCALITY

The fossils at this place were found in a stream bed and were discovered as the result of the construction of a drainage canal. As an aid in interpreting the section through the stream bed the reader may refer to the sketch map of the locality and surroundings shown in Fig. 1. The chief topographic features include a Pleistocene beach and the drainage system of the stream in which the fossils were found. On the east is the narrow body of ocean water known as Indian River and the beach of the present shore line. The ancient beach at this place is low, having an elevation of from 5 to 15 feet above the adjoining flat lands. Both to the north and to the south, however, the ridge formed by the beach becomes more pronounced. This beach, in fact, is a part of the extensive Pleistocene barrier beach which approximately parallels the present shore line for 200 or 300 miles in eastern Florida, and is comparable in origin to the modern or existing ocean beach which lies from one to six miles farther east. The land both in front and back of the beach is prevailingly flat and presents but little variation in level. Such minor elevations as are found tend to assume the form of ridges with a general north-south trend, separated by slight intervening depressions which not infrequently are imperfectly drained. A pronounced north-south ridge or beach is found about 10 miles inland and is known locally as Ten Mile Ridge.

The drainage system of the stream in which the fossils were found is very limited in extent and is controlled largely by the Pleistocene beach. The valley of the main stream, which has a width of from 350 to 500 feet, extends from tidewater in the Indian River into, but not across, this beach. Near the place where the fossils were found the broad valley terminates abruptly

and receives a tributary from the north and another from the south, each of which, however, is of very limited extent. The tributary from the south reaches as far as the railroad station at Vero, a distance of about a half-mile, and one prong also finds its way across the beach and extends as an indefinite drain into the lowlands a distance of possibly a mile. The tributary from the north likewise divides: the west prong, crossing the beach, heads less than a mile to the northwest, while the east prong, which does not cross the beach, continues to the north, paralleling the beach

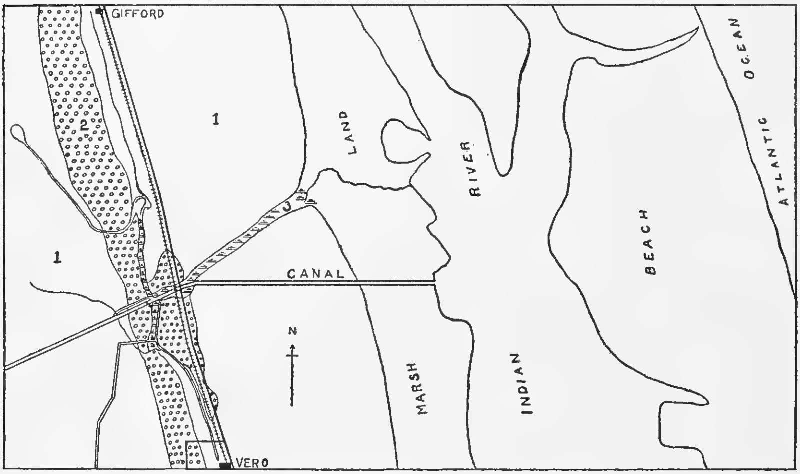


FIG. 1.—Sketch-map showing the locality near Vero from which fossil human remains have been obtained. Scale, 1 inch=4,000 feet. No. 1, pine lands; No. 2, Pleistocene beach; No. 3, stream valley. The human remains were found in the canal bank in this valley, west of the railroad and of the public-road crossing.

to Gifford Station, a distance of about $1\frac{1}{2}$ miles. The whole drainage system is thus very limited, involving only a few square miles, and is in striking contrast to the broad valley which the stream has developed in its lower course. Owing to the breadth of the valley, it may possibly be inferred that at some former time the stream had a larger drainage basin than at present. This, however, does not seem to have been the case, since a pronounced cut or stream channel across the beach, if made, would have persisted to the present time.

The native vegetation is distinctive on the beach, on the flatlands, and in the stream valley. The beach is characterized by spruce pine, *Pinus clausa*, and by an undergrowth of shrubs in which evergreens predominate. The flatlands support a scattered growth of long-leaf pine, *Pinus palustris*, the undergrowth being chiefly saw palmetto. In the stream valley is found a dense timber growth consisting chiefly of hardwood deciduous trees and the cabbage palmetto. The outlines of the valley and of the beach may be very definitely followed by the vegetation, which is controlled in turn by the soil and by the drainage conditions.

The drainage canal, which starts at sea-level on the Indian River, extends due west about one mile before entering the valley of the stream. After following the stream a distance of about 1,000 feet, and having passed under both the railroad and the public road, the canal leaves the valley near the union of the two tributaries, cuts through the beach, and extends inland in a general southwesterly direction about 12 miles. The water level in the canal at low-water stage at the locality where the fossils were found is probably not more than 1 foot above sea, although upon crossing the beach the water level is lifted by means of a spillway to approximately 11 feet above mean sea-level. The land surface for a distance of 12 or 15 miles inland probably nowhere exceeds an elevation of 20 or 25 feet, except Ten Mile Ridge, which is 34 feet above mean sea-level.

DESCRIPTION OF THE SECTION THROUGH THE STREAM VALLEY INCLUDING STRATA NUMBERED 1, 2, AND 3

The section through the stream valley, as exposed in the canal bank, includes three more or less well-marked divisions, which in the present, as in the preceding papers, may be numbered 1, 2, and 3, No. 1 being at the base of the section and No. 3 at the top. In No. 3 of the section are found human remains and artifacts, vertebrate, land and fresh-water invertebrate, and plant fossils. In No. 2 are found human remains, flint spalls, and probably also bone implements, as well as vertebrate, land and fresh-water invertebrate, and plant fossils. From the basal member of the section, a marine deposit, no human remains have been obtained.

To what extent the three divisions of this section represent distinct time intervals, and, on the other hand, to what extent they may intergrade and thus express continuity of time, is discussed subsequently. These divisions are sufficiently well marked to be recognized throughout the greater part or all of the section, and serve as convenient markers in the exact placing of fossils.

The marine deposit, No. 1 of the section, is common to this part of the Atlantic Coast of Florida, and is known to extend both to the north and to the south, being a part of an extensive shallow-water marine formation which borders the Atlantic Coast in Florida for a distance of 200 or 300 miles. This stratum is prevailingly a shell marl, although it contains considerable sand, and in places may consist wholly of sand of medium fine texture. A large exposure, however, will scarcely fail to reveal the presence of the marine shells.

Stratum No. 2, on the other hand, is probably local, representing fill in the stream valley, although its time equivalent, as indicated by the fauna, is found at many localities throughout the state. This deposit in the stream valley averages 3 or 4 feet in thickness, and consists chiefly of rather coarse sand, which at the top as a rule grades into fresh-water marl. Within the stratum, filling holes or channels in the underlying deposit, are found local accumulations of muck, including often wood, sticks, acorns, snail shells, and vertebrate fossils. As a rule the sand near the base of this stratum is light-colored and distinctly cross-bedded, the heavy minerals, including staurolite, ilmenite, and quartz, being deposited in bands and in pockets according to the size of the grain and the specific gravity of the minerals. From 2 to 3 feet above the base of the stratum the sand loses its cross-bedding and becomes dark in color, owing to the inclusion of organic matter. At the top, as has been stated, the sand passes into marl, containing an abundance of land and fresh-water invertebrates.

Stratum No. 3 consists chiefly of layers of muck and vegetable material, alternating with layers of loose, nearly pure, light-colored sand. This alternation of sand and muck is both abrupt and frequent, the layers in places having only a thickness of from one-half to 2 or 3 inches. At the top this stratum grades into a fresh-

water marl which, in places, reaches a thickness of 18 inches. The maximum thickness of this stratum is about 5 feet, although its average thickness is from 2 to 3 feet.

The accompanying sketch, Fig 2, shows the section exposed in the north bank of the canal from the railroad bridge west for a distance of 500 feet. No. 1 is the marine shell marl; No. 2 is the sand stratum which at the base is cross-bedded and at the top passes into fresh-water marl; No. 3 is the deposit of muck and vegetable material with alternating layers of incoherent sand. The letter *b* indicates the location of one of the holes or channels in the shell marl containing muck and driftwood as well as vertebrate, invertebrate, and plant fossils.

In Fig. 3 is shown a section, drawn to scale, of 75 feet of the south bank of the canal, showing the exposure as seen in November, 1916. This section includes that part of the bank west of the entrance of the lateral canal from the south, and thus passes through the exposure at which some of the important fossils have been found. Stratum No. 1 has an approximately even top surface, although at one place near the middle of the section it is cut into rather deeply by stratum No. 2. This place, in fact, represents another of the holes or channels in No. 1 filled with muck and decayed wood. Stratum No. 2 is variable in thickness, being cut into at places by stratum No. 3. Stratum No. 3 as seen in this section is variable both in thickness and in lithologic characteristics. Its maximum thickness near the middle of the section is about 5 feet, the upper 18 inches of which is a fresh-water marl. The top or ground surface of this stratum is cut into at *a* and at *b*. The cut at *a* was probably made in connection with dredging operations. That at *b*, however, is evidently the channel of the modern stream where it cut into stratum No. 3.

At the point *f* in this section the muck and alluvial material of No. 3 grades laterally by an indefinite line into the marl rock. In the writer's former papers the whole section at *e* was referred to stratum No. 2, No. 3 being interpreted as absent at this place. The present exposure apparently indicates that the two feet of marl at *e* is the equivalent of the muck and marl bed of No. 3. A similar section is seen on the opposite or east side of the lateral

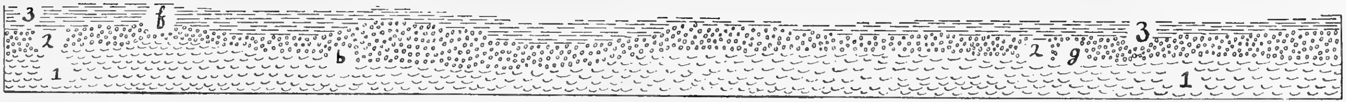


FIG. 2.—Section on the north bank of the canal from the Florida East Coast Railroad bridge west, a distance of 512 feet. No. 1, marine-shell marl and sand; No. 2, fresh-water sand, muck, and marl bed, containing land and fresh-water invertebrate, plant, and vertebrate fossils; No. 3, incoherent sand and muck containing plant and animal fossils. The type specimen of *Canis ayersi* was found at *g*; the type specimen of *Jabiru? weillsi* was found at *b*. Horizontal scale, 1 inch = 73 feet; vertical scale, 1 inch = 25 feet.

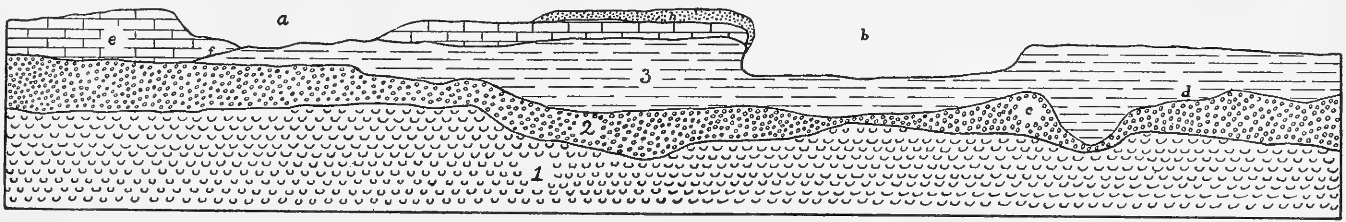


FIG. 3.—Section on the south bank of the canal from the entrance of the lateral canal west, a distance of 77 feet. Vertical and horizontal scale, 1 inch = 11 feet. No. 1, marine-shell marl; No. 2, fresh-water sand; No. 3, stratified deposit consisting of alternating layers of incoherent sand and muck, and grading at the top into a fresh-water marl. Near the place indicated by *f* this stratum grades laterally into the fresh-water marl. The original soil, as well as the full thickness of stratum No. 3, is seen at *h*. The cut at *a* was possibly made in connection with the dredging operations; the cut at *b* indicates the location of the modern stream channel.

canal, and apparently the marl rock of that section may also be referred to stratum No. 3. This part of the section will be more fully discussed subsequently.

The sketch, Fig. 2 of this paper, may be compared with Fig. 6 of the writer's paper in the *Eighth Annual Report of the Florida Geological Survey*, in which is shown a part of the same bank, including the location of the important fossils. Although this part of the canal bank was afterward carried back by excavations a distance of from 5 to 8 feet, the fossils of the former sketch may, as a matter of convenience, be projected on to the present sketch, as has been done in this figure, thus indicating their approximate location with respect to the section as now exposed. Human bones were found in No. 2 at *c* (projected from the former section) and in No. 3 at the general locality indicated by *d*. Pottery and bone implements are found in No. 3 throughout the section.

HUMAN REMAINS AND ARTIFACTS FROM STRATUM NO. 2

The first human bones obtained at Vero were found in the south bank of the canal, 330 feet west of the bridge. In the exposure at this place there is no recognizable break in the section from the base of stratum No. 2 to the marl rock at the top of the section, and in the writer's earlier papers the whole section was referred to stratum No. 2. The new observations recorded in this paper apparently permit the reference of the marl rock at the top of the section to stratum No. 3. If this is true, the human bones at this place in stratum No. 2 are beneath the one and one-half or two feet of marl rock which represents stratum No. 3.

The second lot of human bones from stratum No. 2 were found by the writer in June, 1916. The bones found in place include an astragalus, a cuneiform, and a part of an ilium. Upon sifting the sand in which these bones were imbedded there was obtained in addition two phalanges, a section from a limb bone, and some other human bone fragments. The cuneiform was about 10 inches from the astragalus, and between the two bones at the same level as the astragalus was the scapula of a deer. The ilium was about one foot farther back in the bank. The vertebrate fossils found

in the bank at this locality have been listed in the papers previously published.

The flints obtained from stratum No. 2 include a spall found in place 3 feet east of the human bones listed in the preceding paragraph, and about one foot farther back in the bank. Upon passing the sand through a sieve five additional flint spalls were obtained from this stratum, one of which was found about 10 feet

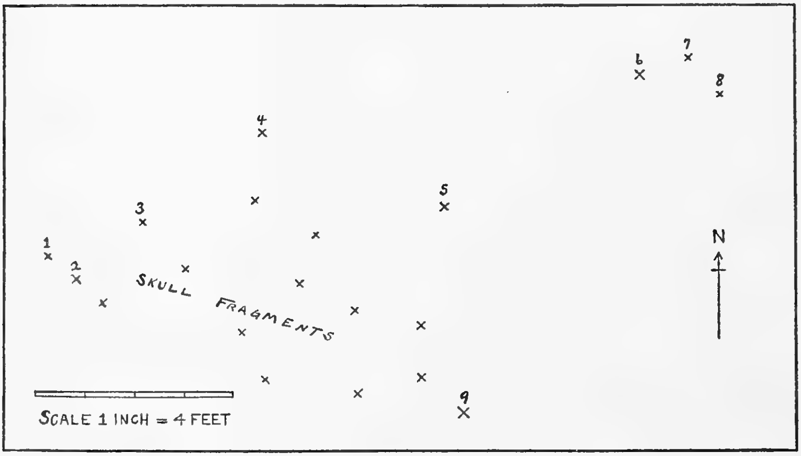


FIG. 4.—Ground plan showing the location of human bones found in the canal bank at Vero in April and in June, 1916. The canal bank at this place faces approximately northwest and those bones, the location of which is indicated by Nos. 1–5, and also several of the skull fragments, were collected in April. Those bones numbered 6–9 and a few skull fragments were collected in June. Among bones not specially numbered are a part of the right femur and an incisor tooth found near No. 9, and a part of a metatarsal found near No. 2. The bones indicated by Nos. 1–5 and No. 9 and several of the skull fragments were found on or near the contact line of strata Nos. 2 and 3. Those bones indicated by Nos. 6–8 were found in stratum No. 2. Bones taken from the caving of the bank and from siftings are not shown in this plan. Index to bones: 1, left ulna; 2, a part of the shaft of the same bone; 3, left femur; 9, a part of the shaft of the same bone; 4, radius; 5, metatarsal; 6, astragalus; 7, external cuneiform; 8, part of ilium. The place in the bank of bones Nos. 1, 3, and 4, and bones Nos. 6 and 7, is shown in photographs previously published.

farther west. From these siftings were obtained also one nearly complete small bone implement and a piece of a second bone implement. Markings on bones from this stratum, which may have been made by tools, have been described in the papers to which reference has been made.

The spalls found in this stratum have been placed in the hands of Dr. George Grant MacCurdy, who has consented to report upon them. It is evident that these flints are not of local origin, the nearest known outcrop of a flint-bearing formation being more than 100 miles to the northwest. The flint spalls are sharp-edged and quite unworn, indicating that they have been transported no great distance by water. The small flint pebbles occasionally found in this deposit, on the contrary, are rounded and well worn, there being no intermediate stages between the worn pebbles of the deposit and the sharp-edged spalls.

HUMAN REMAINS AND ARTIFACTS IN STRATUM NO. 3

Three finds of human skeletal material are reported from stratum No. 3. In each instance the bones lay at the contact line between strata Nos. 2 and 3, and hence may belong to No. 2 rather than to No. 3. The first of these discoveries was in the south bank of the canal at the locality shown in Fig. 3. The bones obtained at this place include the right and left ulna, part of a humerus, a scapula, two incisors, parts of right and left femora, a radius, part of a jaw, two metatarsals, and a considerable portion of the skull, the pieces of which were dissociated and scattered. All of these bones were on or very near the contact line between Nos. 2 and 3, and, as they are near the place where human bones were found in No. 2, they may have been derived from stratum No. 2 and, as the writer has previously suggested,[1] may pertain to the same individual as the bones found in No. 2.

The second discovery of human remains referred to stratum No. 3 was made by Isaac M. Weills, who in April, 1916, obtained a single human toe bone from the base of stratum No. 3 on the north bank of the canal, 419 feet west of the bridge. A third discovery of human skeletal material from this stratum was made also by Mr. Weills, who in June, 1916, obtained a single human tooth from the base of No. 3, on the north bank of the canal, 450 feet west of the bridge. All of the human skeletal material obtained at Vero has been placed in the hands of Dr. A. Hrdlička, who, it is hoped, will discuss their relation to the modern races.

[1] *Fla. State Geol. Surv., Eighth Annual Report,* p. 142, October, 1916.

In addition to the skeletal material a large number of artifacts have been obtained from stratum No. 3. A small arrowhead was taken from this stratum by Mr. Weills in April, 1916. A rather large arrowhead was obtained from near the base of the deposit by the writer in June, 1916. Two spalls have been found near the contact line of strata Nos. 2 and 3, and four others have been obtained in siftings from No. 3. From this deposit has been taken about two dozen bone implements, as well as one wood implement and one object, probably a section from an alligator tooth, which apparently was used as an ornament. Broken pottery is not uncommon in this stratum, about one hundred or more pieces having been collected. Neither the pottery nor the bone implements are restricted in their occurrence. On the contrary, they are common to this horizon and are found at places where the horizon reaches its maximum thickness and retains its covering of marl rock, as well as at other places where the stratum is thinner and has been cut into by the recent stream bed.

FOSSILS FROM STRATUM NO. 1

Stratum No. 1, as previously noted, is a marine deposit in which invertebrates are abundant and well preserved, the natural coloration of the shells being in some degree retained. No vertebrate fossils are known from this stratum at this locality, although from shell marl, probably equivalent in age, at West Palm Beach the writer has obtained the distal end of the humerus of a camel.

A collection of invertebrates from this horizon was made by the writer in 1915 and submitted to Dr. T. W. Vaughan, in charge of Coastal Plains investigations of the United States Geological Survey. The mollusks of this collection have been identified under Dr. Vaughan's direction by Mr. Wendell C. Mansfield. Of forty-two species definitely identified (17 gastropods and 25 pelecypods), all, according to notes kindly supplied by Mr. Mansfield, are identical with the species believed to be now living. One species only, an *Arca*, is regarded by Mr. Mansfield as intermediate between the recent *A. ponderosa* and the probably extinct *A. limula*. It appears, therefore, that the marine molluscan fauna of

stratum No. 1, as well as the land and fresh-water molluscan fauna of stratum No. 2, is essentially identical with the modern molluscan fauna. In this respect the invertebrates are in very decided contrast to the vertebrates among which are many extinct species.

FOSSILS FROM STRATUM NO. 2

To the mammals previously listed from stratum No. 2[1] may now be added the genus *Mylodon*, evidence of the presence of which in stratum No. 2 was obtained in connection with the conference of geologists and anthropologists held at Vero in October. Among other important fossils added in November were about thirty bones from the skeleton of the large extinct wolf, *Canis ayersi*. These bones were found in the canal bank, from 7 to 10 feet west of the place from which the skull and femur which served as the type specimen of the species were found, and probably belong to the same individual. From the north bank of the canal, 460 feet west of the bridge, was obtained a practically complete skull of the tapir, lacking only the lower jaw. From the south bank of the canal at the railroad bridge was obtained about $4\frac{1}{2}$ feet of the tusk of a proboscidian. This tusk was found at the same place and probably pertains to the mastodon, a part of the skull of which had previously been secured. The recovery of these fossils was due chiefly to high water in the canal, following heavy rains at the close of October. The water cleaned the banks of the canal, thus facilitating both the examination of the section and the collecting of fossils. To the birds, of which two species were previously known, a third species, represented by a humerus, may now be added. To the other fossils of this stratum—the plants, invertebrates, fishes, batrachians, and reptiles—no species so far as known are added in the new collections. The land and fresh-water invertebrates, which include about twenty-eight identifiable species, have been determined as previously reported by Dr. Paul Bartsch and are found to be identical with the modern species. The turtles have been identified by Dr. O. P. Hay and have been found to include chiefly extinct species.

[1] *Fla. Geol. Surv., Eighth Ann. Rept.*, p. 158.

The following is a list of the mammals of stratum No. 2, which fully establish the Pleistocene age of the deposit:

Didelphis virginiana	Mammut americanum
Megalonyx jeffersonii	Elephas columbi
Mylodon sp.	Neofiber alleni
Chlamytherium septentrionalis	Sylvilagus sp.
Dasypus sp.	Sigmodon sp.
Equus leidyi	Cryptotis floridana
Equus complicatus	Blarina sp.
Equus littoralis	Smilodon sp.
Tapirus sp.	Hydrochoerus sp.
Odocoileus sp.	Procyon lotor
Bison sp.	Lutra canadensis
Peccary, indt.	Canis ayersi
Camel, indt.	

The Pleistocene fauna of this horizon is found at many places in Florida. Some of the localities on or near the Gulf Coast from which a typical representation of this fauna has been obtained are Peace Creek, Sarasota Bay, the Caloosahatchee River, the Withlacoochee River, and cave deposits at Ocala. Other localities on or near the Atlantic Coast from which this fauna is known include Daytona, Fellsmere, Palm Beach, Eau Gallie, and St. Augustine. The mammalian species known from these different localities have been listed by the writer in a paper recently published.[1]

FOSSILS FROM STRATUM NO. 3

The fossils of stratum No. 3, which include plants, insects, land and fresh-water mollusks, fishes, batrachians, reptiles, birds, and mammals, have not been fully identified, and hence cannot be discussed in detail at this time. Mr. E. W. Berry has kindly undertaken the identification of the plants. The insects, of which only a few have been obtained, have been submitted to Professor H. F. Wickam. The land and fresh-water mollusks are few in number, and presumably are identical with the modern species, since those of the older deposit, stratum No. 2, according to Dr. Bartsch, are not separable from the modern forms. The fish

[1] "Fossil Vertebrates from Florida; A New Miocene Fauna; New Pliocene Species; the Pleistocene Fauna," *Fla. Geol. Surv., Eighth Annual Report,* pp. 77–119, Pls. 10–14, 1916.

remains, which are fragmentary, are in the hands of Dr. Charles R. Eastman. The birds of this deposit are being studied by Dr. R. W. Shufeldt.

The turtles from stratum No. 3 have been studied by Dr. O. P. Hay, who finds that six species are present. Of these six species three are extinct, one is sub-specifically different from the modern, and two are apparently not separable from the modern species. The mammals, the identification of which has been approximately completed, are more abundant than the turtles. The species of mammals recognized include the following:

Didelphis virginiana	Scalopus sp.
Chlamytherium septentrionalis	Vulpes sp.
Dasypus sp.	Canis cf. latrans
Odocoileus sp.	Procyon lotor ?
Neofiber alleni.	Lutra canadensis
Sylvilagus sp.	Lynx sp.
Sigmodon sp.	Ursus, indt.
Neotoma sp.	

The extinct genus of armadillo-like animals, *Chlamytherium*, is represented by well-preserved, uneroded dermal scutes. The armadillo, *Dasypus*, is likewise represented by dermal scutes. The fox, which differs from the species at present known in Florida, is represented by a part of the lower jaw containing two premolar teeth, and by a single premolar tooth obtained from the fresh-water marl rock on the south bank of the canal, 335 feet west of the bridge. The rock at this place, as previously mentioned, has heretofore been placed in stratum No. 2, but at present is regarded as probably equivalent to stratum No. 3. *Canis* cf. *latrans* is represented by a part of the upper jaw containing the carnassial tooth. The lynx is represented by a jaw and a tibia. Parts of the teeth of *Elephas columbi* and of *Mammut americanum* are by no means uncommon in this stratum. The tapir and horse are also represented, although by fragmentary material.

Dr. R. W. Shufeldt has very considerately submitted an abstract of his report on the fossil birds found at Vero, with permission to insert it here in advance of the publication of the report as a whole. The abstract includes all bird material obtained at Vero except a

stork, *Jabiru weillsi*, previously described by the writer, and a left humerus of a passerine bird related, according to Dr. Shufeldt, to the meadow larks. These two species and the first of the following list, No. 7550, are from stratum No. 2 of the section. All other birds of this list are from stratum No. 3.

REPORT ON FOSSIL BIRDS FROM VERO, FLORIDA, BY R. W. SHUFELDT

No. 7550. The right humerus, nearly perfect, of a teal. This bone I have carefully compared with all the humeri of our smaller existing ducks of various genera. It comes quite close to *Querquedula discors*, but belonged to a different species of that genus. I propose to describe it as *Querquedula floridana*.

No. 6934. This is the distal moiety of the right *tibio-tarsus* of a barn owl (*Tyto pratincola*). The condyles are slightly chipped off posteriorly.

No. 6773. Distal half of the right tarso-metatarsus of a water bird; probably a *Larus*, about the size of *Larus atricilla*. Whether this belonged to the same specimen as the next (No. 6933) I cannot say.

No. 6933. Left carpo-metacarpus of some tern or gull; I am inclined to believe, from the slight preponderance of characters, a gull of the genus *Larus*. It was a considerably larger species than *Larus atricilla*, but comes close to it. It was also a larger bird than *Stirna maxema*. I have compared it with the corresponding bone in many species of terns and gulls. Apparently it does not represent any of our existing forms. For this doubtless extinct species I propose the name of *Larus vero*.

No. 7552. Humerus (right side), imperfect; head of bone not recovered. Length of fragment 8.35 cm. No. 6797. The shaft of an ulna of a large bird. No. 6932. Piece of a long bone, the shaft (humerus?) of some large bird. These three specimens too fragmentary for reference.

No. 7005 (in two pieces; smaller fragment not numbered). The left ulna of *Cathartes aura*.

No. 6774. The distal two-thirds of the left tarso-metatarsus (imperfect), of some heron (*Ardea*), larger than *Nycticorax n. naevius*. Not quite perfect enough for exact reference.

No. 6932. The distal portion of the left tarso-metatarsus of *Ardea herodias* (adult); the trochleae slightly abraded posteriorly.

No. 7554 (including three vertebrae). The two small vertebrae are from a bird, and belong to the distal end of the cervical chain. It is hardly possible to say to what kind of bird they belong, though they agree more or less with the posterior cervical vertebrae of several average waders. The large elongate vertebra is from the cervical region of another wader, a true heron of the genus *Ardea*. I have compared it with the corresponding bone in the neck of all our medium-sized waders, as herons, spoonbills, egrets, and many others, and I find that, in all particulars, it comes nearest to the same vertebra in *Herodias*

egretta. However, I would hardly feel justified in making a new species of this, unless it was associated with other bones belonging to the same skeleton. I would suggest, therefore, that it be set aside to await the discovery of additional material from the same locality and the same excavation.

In this little lot there still remains the distal extremity of a small right tarso-metatarsus, which is quite perfect as far as it goes. It belonged to some sort of average-sized wading bird, perhaps after the heron order, or a near ally. I have compared it with the corresponding part in some thirty skeletons of existing birds; but, while it comes pretty close to some of them, it presents departures of such a nature that it does not agree with any of them. I am not prepared to describe it as coming from a new and extinct bird; but I would suggest that it be set aside to await the discovery of additional material from the place where it was found.

No. 7551. This is the distal portion of a right tibio-tarsus of a heron somewhat smaller than *Ardea herodias*, but specifically distinct from it. The condyles are considerably abraded, but otherwise the specimen is perfect as far as it goes. The intercondylar valley is narrower and shallower than we find it in *Ardea herodias*, and the anterior tendinal groove in the fossil rapidly contracts as it proceeds up the shaft, to become very narrow about 2 cm. above the osseous tendinal bridge. This is not the case in *Ardea herodias*, wherein the anterior surface of the shaft in that locality is flat, and barely exhibits any tendinal groove. There are a few other points of difference, which, taken in connection with what is set forth above, inclines me to believe that this bone belonged to a heron of the genus *Ardea*, of about the same size as the existing *Ardea herodias*, but specifically distinct from it. For this apparently extinct heron I here propose the name of *Ardea sellardsi*.

No. 7000. An imperfect distal third of the right tarso-metatarsus of a large wader. Unfortunately the trochleae are nearly all fractured off; still the characters of this bone are so pronounced that I have no hesitation in referring it to some species of *Mycteria*, and it probably belonged to a wood ibis, *Mycteria americana*, with which I have compared it. So far as the fragment goes, it does not seem to offer a sufficient number of characters to separate it from that species.

It is thus found that stratum No. 3 of the section at Vero contains extinct species of each of the three vertebrate classes—reptiles, birds, and mammals. Since this deposit, No. 3, rests upon the fossiliferous stratum, No. 2, it becomes necessary to inquire to what extent these fossils may possibly have washed from the underlying deposit. With regard to birds, those of No. 3 are more abundant both in specimens and in species than are those of No. 2. Moreover, the bird bones are fragile and would not withstand washing from

one formation to another. That the extinct turtles do not represent inclusions from the older formation is evident by the fact that practically complete carapaces are found, which in some instances are so delicate as not to stand so much as turning over without being broken. That the mammals referred to No. 3 are normal to that deposit is indicated both by the abundance of the bones and by their condition of preservation.

INTERPRETATION OF THE SECTION

It is desirable in this connection to consider the interpretation of the section as a whole, especially as to whether or not an appreciable period of time intervened between the deposition of divisions 1 and 2 of the section, and also between divisions 2 and 3. As a rule, it is possible to recognize the dividing line between the marine stratum, No. 1, and the fresh-water deposit, No. 2. At such places, even though the marine shells are lacking in No. 1, there is a change in the texture, and usually also in the color, of the sand. Moreover, one finds rather commonly irregularities at the top of No. 1, which are due to stream wash. Occasionally there are also depressions or holes in the top of No. 1. Such holes, so far as observed, as previously stated in this paper, contain muck and decayed wood and sticks. However, notwithstanding this apparently well-marked break, there are other places where the dividing line between Nos. 1 and 2 is evident neither by the change of texture of the sand nor by any change in color. At such places deposition appears to have been continuous from stratum No. 1 into stratum No. 2. On the other hand, there is at all places evidence of the change from marine to fresh-water deposition. Since the fossils of No. 1 are marine, while those of No. 2 are land forms, there is little opportunity of connecting the two divisions by means of the fauna. Aside from the one camel bone obtained at West Palm Beach, no land animals are known from No. 1 of this section.

In the preceding papers the writer has commented upon the abrupt break which normally exists between strata Nos. 2 and 3, a break which it seemed possible might be taken to indicate a considerable interval of time. The later observations of this section,

however, as previously stated in this paper, indicate that a part of the section heretofore referred to No. 2 is possibly the equivalent of No. 3. It seems not impossible, therefore, that the break between divisions 2 and 3, which is so evident throughout a large part of the section, may be due to local re-working by the stream of its own bed in Pleistocene time, and that the deposit designated as stratum No. 3 is itself a phase of stratum No. 2, being analogous to the smaller deposits of muck and decayed wood found near the base of No. 2, which are known to be inclusions within that stratum. On the question of the interrelation of the three divisions of the section, however, it will perhaps be necessary to await the accumulation of further evidence, both stratigraphic and paleontologic.

RELATION OF THE HUMAN REMAINS TO THE ASSOCIATED FOSSILS

It will scarcely be maintained that the human remains and artifacts obtained from stratum No. 3 are otherwise than normal to that deposit. Their abundance, their general distribution, and their presence within and at the base of a stratified and undisturbed deposit preclude any reasonable contention that they are otherwise than contemporaneous with the associated materials of the deposit. The study of the fossils of this stratum, although not yet completed, has brought to light the presence of a considerable number of extinct species which suggest the reference of the deposit to the Pleistocene period.

Special interest is attached to the human remains and artifacts from stratum No. 2, this being the oldest deposit from which human material has been obtained. This stratum is easily recognized, and at the present time may be followed on both the north and south banks of the canal through the whole section. The vertebrate fauna by which the Pleistocene age of the deposit is determined is also well represented in the collections that have been made at this locality. That the human bones are fossils normal to this stratum and contemporaneous with the associated vertebrates is determined by their place in the formation, their manner of occurrence, their intimate relation to the bones of other animals, and the degree of mineralization of the bones. The presence of flint spalls, and the probable presence of bone

implements add support to the evidence obtained from the bones themselves.

The place of the human bones in the formation affords a strong argument for their contemporaneity with the associated fossils. Those human bones found in the south bank of the canal, 330 feet west of the bridge, lie beneath 18 inches of marl rock. The human bones found in the same bank, 462 feet west of the bridge, lie beneath 4 feet of stratified deposits consisting of alternating layers of sand and muck, which could not have been dug through and replaced without interrupting the continuity of the strata. Moreover, the presence of the muck, as well as the conditions of preservation of the plant remains, indicates that this locality has been continuously moist since the materials of both Nos. 2 and 3 were deposited. Aside from the improbability of locating a grave in a muck bed, it is probably impossible without special appliances to dig a grave through an undrained muck bed on account of the presence of ground-water. If it be suggested that the human remains in stratum No. 2 represent a burial, it must be recognized that the reference is not to a recent burial, but to a burial antedating the deposition or existence of stratum No. 3 of the section, and hence to an event that occurred probably within the Pleistocene period of time. There is, however, strong evidence that the human remains in this deposit do not represent a burial by human agency, but are fossils normal to the stratum, having been included in the earth in the same way and at the same time that the other bones were buried in the accumulating deposits.

The manner of occurrence of the human bones is entirely similar to that of the other vertebrate fossils. Whole skeletons are not found, and, indeed, complete bones are by no means common. On the contrary, the human bones as well as the bones of the other animals are scattered, imperfectly preserved, and frequently broken. The breaks in the bones are as a rule sharp-edged, and it would seem that in the case both of the human and of the other vertebrates the bones were more or less disturbed after they had lost enough of the organic matter to become sufficiently brittle to break as they were moved about by water before reaching their final resting-place. An illustration of the way in which the

bones were broken is afforded by a fragment from the shaft of a human limb bone, No. 6958. This piece of bone is broken with a sharp fracture at each end. The breaks are old and were made at the time that the bone was imbedded in the sand. The intimate association of the human and other fossils is difficult to explain except upon the recognition of their contemporaneity. The human astragalus and cuneiform were separated by a space of about 10 inches, and between them at the same level as the astragalus was the scapula of a deer. Bones from the skeletons of other animals were near by in the same stratum and have been described in the writer's previous papers.

In the number of bones that have been obtained representing a single individual there is observed no important difference between the human and the other animals. The most nearly complete skeleton that has been obtained is that of an alligator. The next largest number of bones found, about thirty or thirty-five in number, from the skeleton of a single individual are those of the extinct wolf, *Canis ayersi*. Among the most perfectly preserved individual bones that have been obtained from the deposit are those of the bird, *Jabiru? weillsi*, the femur of a horse, the lower jaw of *Chlamytherium*, and part of the skull and tusk of a proboscidian. Entirely surpassing any of the human bones in perfection of preservation is the skull of the extinct wolf and the skull of the tapir. The tapir skull, so far as the writer has been able to learn, is the first approximately complete skull of this animal that has been obtained from the Pleistocene of North America.

The degree of mineralization of the human bones is identical with that of the associated bones of the other animals, a fact that has been brought out in the papers previously published by the writer. The spall found in place in this stratum, as well as the several other flints obtained from siftings, is totally unlike any flint pebbles in the deposit. The reasonable explanation of the presence of these spalls in this stratum is that they washed in from the near-by land surface, together with the other materials of the deposit. In other words, they pertain to the Pleistocene period and were washed into the deposit at that time. The bone

implements, although obtained from the siftings and hence not seen in place, are, with little doubt, to be attributed to the same source.

The presence of man in the Pleistocene of Europe has long been known, and his assumed absence from the Pleistocene of America is based entirely on negative evidence. How insecure as a basis of argument in paleontology is negative evidence has been repeatedly demonstrated, and new groups with Old World affinities are constantly being recovered from the North American formations. A striking illustration is the eland obtained in 1913 by Gidley from the Pleistocene of Maryland, the relationship of which is closer to the modern eland of Africa than to any other known species, the dispersion and migration of the group having probably occurred during the Pleistocene period.[1] Another illustration is afforded by the bears. Heretofore, it has been assumed that members of the bear group were comparatively recent migrants to the New World, but during the past summer representatives of the true Ursidae were obtained practically simultaneously in Oregon[2] and in Florida.[3] Numerous other illustrations might be given, and in fact the rapidity with which new species are being obtained and described is evidence of our heretofore imperfect knowledge of the Pleistocene faunas. Man lived with and hunted *Elephas primigenius* in Europe, and it is not improbable that he may have followed the spread of that species to America. The evidence obtained at this new locality in Florida, supplementing the less positive evidence that has heretofore been available, affords proof that man reached America at an early date and was present on this Continent in association with a Pleistocene fauna.

[1] James Williams Gidley, "An Extinct American Eland," *Smithsonian Miscellaneous Collections*, LX, No. 27 (March, 1913).

[2] John C. Merriam, Chester Stock, and Clarence L. Moody, "An American Pliocene Bear," *Univ. of Cal. Publ.*, X, No. 7 (November 1, 1916).

[3] E. H. Sellards, "Fossil Vertebrates from Florida," *Fla. Geol. Surv., Eighth Annual Report* (October, 1916).

INTERPRETATION OF THE FORMATIONS CONTAINING HUMAN BONES AT VERO, FLORIDA

ROLLIN T. CHAMBERLIN
University of Chicago

The formations of the locality involved in the interpretation of the age and relations of the fossil remains of man found near Vero, Florida, have been clearly described in the preceding paper by Dr. Sellards. The surface aspect of the region is plane and flat, relieved slightly by low beach ridges, gently rising dunes, and

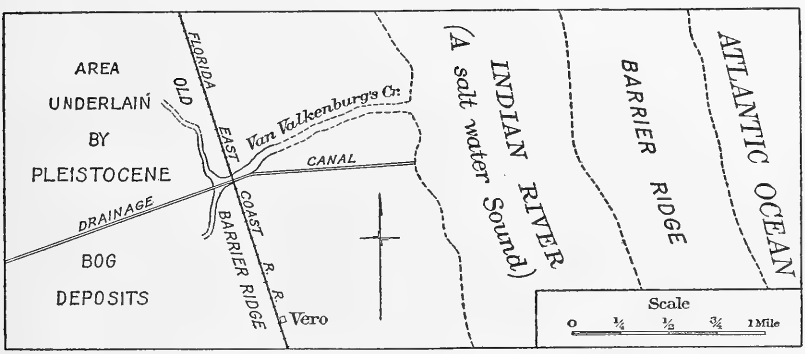


FIG. 1.—Rough sketch showing merely the general relations of the features discussed in the text.

shallow drainage flats, none of which are impressive features of the landscape, though all contribute valuable criteria to the interpretation. In its immediate bearings on the problem raised by the occurrence of human remains mingled with extinct vertebrates, the critical feature of this plain is the broad, shallow valley of Van Valkenburg's Creek, whose former course—now much obscured by the recently dug drainage canal—is indicated in Figs. 1 and 2. It was in the bottom deposits of this wide stream channel, or in those of its predecessor, that the human bones in question were found. The past workings of this stream, therefore, require the

closest scrutiny. But before attempting to interpret the history of the stream, let us review briefly the geologic section at Vero, though we have little occasion to depart from the careful description of Dr. Sellards.

Beneath the stream deposits, as well as beneath the whole region under consideration, the oldest beds exposed to view belong to the Anastasia formation, a striking marine shell marl, often known as "coquina" rock. Composed almost entirely of shells,

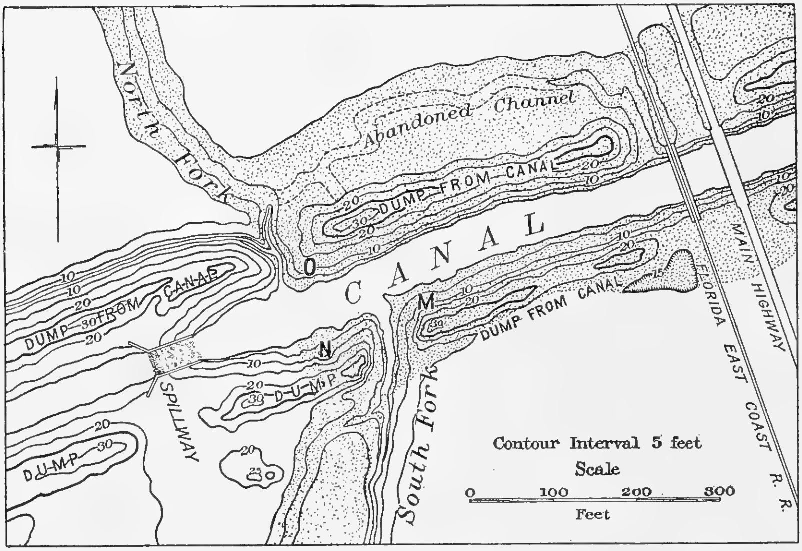


FIG. 2.—Detailed map of the locality where the human bones were found. The canal and the resulting dump piles have done much to change the original topography. The dotted area represents the flood plain of Van Valkenburg's Creek as its appears to have been just prior to the digging of the canal. The first human skeleton was found in formation No. 2 at point marked *M*, the second at point *N*, while human relics were found in formation No. 3 at point *O* as well as also near *N*.

in most cases but little fragmented, its identity is always clear, and it thus affords a most excellent datum plane at the base of each section studied. It is Dr. Sellards' formation No. 1, and is assigned to the Pleistocene. In its upper portion it grades into beach sands containing here and there lenses and streaks of shells, and these, in turn, pass upward almost imperceptibly into fresh-water or wind-blown sands. This formation underlies both the area of Van

Valkenburg's Creek and the adjacent country, and thus far the sections are the same, but above this horizon the channel section and the upland, or country, section are totally unlike and will be described separately.

THE SECTION OF THE CREEK BOTTOMS

This is the section described by Dr. Sellards. It is now well exposed in the walls of the drainage canal which, for several hundred

FIG. 3.—The drainage canal, looking southwest from the Florida East Coast Railroad bridge to the spillway.

yards, cuts through the deposits of the old creek bottoms. Resting upon the eroded surface of formation No. 1, sometimes lying directly upon the coquina rock, sometimes resting upon the beach sand, or shore phase of No. 1, is Dr. Sellard's formation No. 2. It is, as he has described it, a cross-bedded, river-washed sand, partly white, partly stained brown by organic matter, and containing partially decayed wood and muck. At the top, in places, there is a fresh-water, clayey marl. This formation contains human bones essentially *in situ*, beyond reasonable doubt, together

with the scattered bones of many extinct vertebrates, as maintained in the previous paper. It is, therefore, the critical formation of the section, and upon its age and mode of origin the case of Pleistocene man stands or falls.

Above formation No. 2, and, at most points, sharply separated from it by a clear-cut line of erosion, is an alluvial deposit, formation No. 3 of Sellards. This is composed of swamp muck in many layers, interstratified with layers and lenses of coarse sand. Its top is the present flood-plain surface of Van Valkenburg's Creek.

INTERPRETATION OF THE CREEK SECTION

Following the deposition of the marine coquina, a withdrawal of the sea gradually brought this region into the horizon of terrestrial action. In the transition, beach conditions prevailed, resulting in sandy deposits, partly marine, partly terrestrial. These finally gave way to eolian sands. An interval of unknown duration followed. At some later time a stream occupying essentially the same course as that which, just prior to the construction of the canal, was followed by Van Valkenburg's Creek excavated a channel which, in some places, was cut through into the coquina. The notable width of this channel in proportion to its very shallow depth—which was limited by sea-level—suggests that erosive action was in progress for a considerable time at least. But as Dr. Sellards has remarked, tidal scour may have been an accessory factor in the development of the breadth of the channel. There are today in the strip of coast between Sebastian and Eau Gallie several such broad, shallow channels up which the tide runs. But if tidal scour is appealed to, it must be interpreted so as to be consistent with the fact that there were deposited in the Vero channel, not only muck and washed sands, but also human bones, together with many scattered bones from a variety of extinct vertebrates. The interpretation must also be in harmony with the specific fact that the human bones were found to be notably less scattered and fragmentary than the bones of the extinct vertebrates.

Some erosion of the surface of this No. 2 formation seems clearly to have occurred, since its upper surface is a sharp line,

and this is most naturally interpreted as implying change of attitude or of relations, as well as an erosion interval. After such erosion it was covered by the alluvial deposit, No. 3. Because of the large proportion of muck, and the extremely rapid shifting from muck-accumulating to sand-depositing conditions, as revealed by the many alternating layers and lenses of sand and muck, this

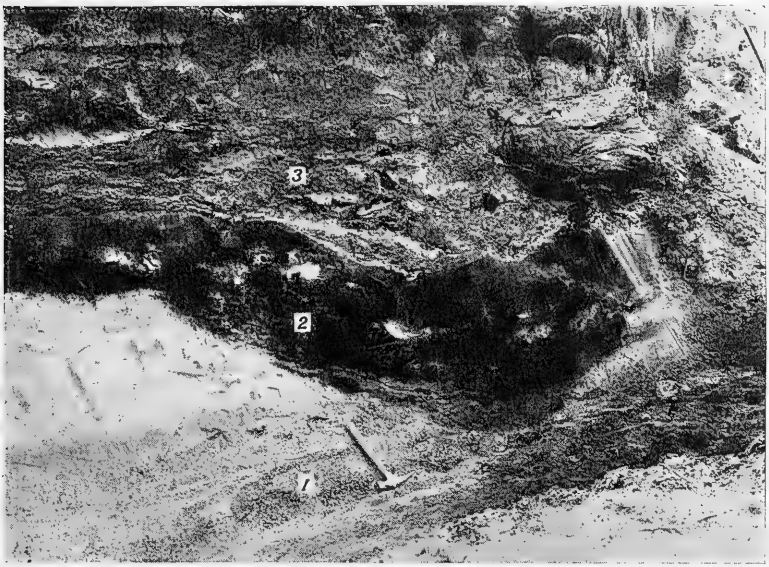


FIG. 4.—The creek section freshly exposed by cutting back into the south bank of the drainage canal at a point about 440 feet southwest of the railroad bridge: 1 represents the "coquina" rock grading upward into light-colored sands; 2 is Sellards' formation No. 2, which is here sand largely stained dark brown; note that it fills a trench cut in No. 1; 3 is Sellards' formation No. 3, consisting of alternating muck and coarse sands. Large log projects conspicuously on the right.

is interpreted as a flood-plain deposit. Its upper surface constituted the flood-plain of Van Valkenburg's Creek prior to 1913, when the drainage canal was dug.

THE UPLAND OR COUNTRY SECTION

Downstream.—Though the surrounding country is not elevated, the general section outside the valley of the creek may be designated the upland, or country, section. Downstream from the

locality where the human bones were found the country section adjacent to Van Valkenburg's Creek commences with the coquina rock at the bottom, just as does the section of the creek bottom. The coquina beds are followed by 2–5 feet of variously tinted sands. An orange-brown, ferruginous sand is a very persistent phase. These sands become dark-brown to blackish at the top, but are not very firmly indurated. At most points this sandy deposit forms the present surface, but in some isolated areas it is capped by a pondlike deposit of drab-colored, clayey, fresh-water marl. As this is being utilized for road material, the clay marl areas have been opened up to view and their extent is well known.

The south bank of the canal one-third of a mile east of the Florida East Coast Railroad bridge gives the following section:

o) Drab-colored, clayey, fresh-water marl.......................... 3 ft.
n) Dark-brownish, mottled sand, lighter colored below, getting darker above and at the top showing nearly black material, indicating an old soil line.. 2 ft.
m) Marine shell marl (coquina).................................. 1 ft.

The tract represented by this section lies nearer the coast than the locality where the human bones were found in the stream deposits, and hence has less specific bearing on our problem than the upland section of the tract adjacent to the creek *above* the critical locality.

Upstream.—The upstream section was found to be somewhat different from the coastward section as given above. Approximately 200 feet southwest (upstream) from the point where the human relics were discovered the waters of the drainage canal pass over a spillway and drop about 9 feet. This spillway is west of the junction of the two tributary branches of Van Valkenburg's Creek and lies outside the creek valley. For the first half-mile west of the spillway the canal has been cut through the following succession of beds:

d) Pure-white, coarse-grained, wind-blown quartz sand............. 4–7 ft.
c) Soft, spongy, peaty layer, containing many partially decayed roots; in places absent.. 0–6 in.
b) Dark-brown to true-black, firmly indurated sand or sandstone; cemented by ferric hydroxide and organic matter, but the color of iron staining is largely obscured by the organic black........... 2–4 ft.

a) Brown sand gradually losing its dark stain and passing downward into a reddish-brown sand stained by iron oxide, and finally grading into a buff sand below, which is of finer grain than that above, and may possibly be marine.................................... 3–4 ft.

There is no sharp division between (*a*) and (*b*).

For at least another half-mile west the section changes in no essential feature except that the wind-blown sand (*d*) gradually

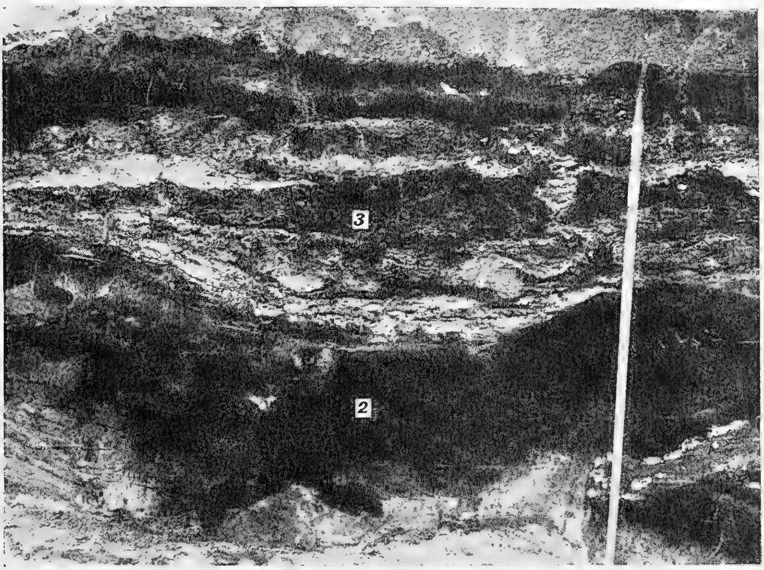


FIG. 5.—The creek section on south bank of drainage canal, 465–70 feet from the bridge. This face, now dug back many feet from the original drainage canal bank, is approximately the spot where the second human skeleton was found in formation No. 2 (marked *N* on map, Fig. 2). Formations Nos. 2 and 3 displayed.

thins until, at one mile from the spillway, there are barely two feet of it. The coquina rock does not appear above the water-level in the canal during the first mile west of the spillway, though it is said to reappear some distance farther west.

INTERPRETATION OF THE UPLAND SECTION

Following the deposition of the marine coquina beds, semi-marine, semi-terrestrial beach sands, and, later, eolian sands accumulated to a thickness of perhaps 6–8 feet over much of the

country immediately northwest of Vero. In spots the thickness was less, but at other points, no doubt, dunes as well as beach ridges made its total more than this. A widespread peaty layer at the top of this formation strongly suggests that, following the deposition of these sands, bog conditions existed for a period in the area west of the spillway. The upper two or three feet of the sands of layer *b* are very firmly cemented by iron oxide, and are

FIG. 6.—Section of uplands, exposed in north bank of drainage canal, one-third mile southwest of spillway: *B* represents layer *b*, consisting of indurated black sand or sandstone, capped in the left half of the picture by peat (layer *c*); *D* is layer *d*, white eolian sands, resting upon the Pleistocene bog surface. Above is the material excavated in making the canal.

deeply stained by organic matter, implying that this horizon constituted the subsurface for a long time. Iron oxide cement is, as is well known, common in bog deposits. A reason for an extensive wet area, or bog, to the west of the spillway is readily found in a broad beach ridge near the spillway which interfered with the drainage of the tract lying west (see Fig. 1).

The present coast, in a way, serves as an example of similar relations. The east coast of Florida is flanked by a barrier sand

ridge for 300 miles; for over 100 miles the barrier incloses a strip of water between it and the mainland, known as the Indian River, though it is really a salt-water sound. Paralleling the present coastal barrier and the Indian River behind it is an older barrier ridge which crosses the canal near the spillway and runs for many miles both north and south of Vero. To the west of it, before the drainage canal was dug, the region was frequently

FIG. 7.—The present upland country southwest of the spillway. The area of the Pleistocene bog. Drainage canal in foreground with tributary canal in middle distance. Lumps of the black sandstone conspicuous upon dump piles of both canals.

under water after storms, according to testimony, and in earlier times it presumably was more continuously marshy, since it more nearly approached the present condition of the Indian River.

But with uplift, or withdrawal of the sea, the marsh was gradually drained, and a thin covering of wind-blown white sand drifted over the old bog surface, burying it to a depth of several feet. This wind-blown sand forms layer *d* and constitutes the present upland surface.

CORRELATION OF CREEK-BOTTOM SECTION WITH UPLAND SECTION

For the complete history of the district it is necessary to correlate the creek-bottom section with the upland, or country, section. The coquina is common to both and serves as a base of reference. If we turn to the upland section as it is developed just west of the junction of the two forks of Van Valkenburg's Creek, we observe that the most striking feature there shown is the almost perfectly black, indurated sand bed, or sandstone, which forms a persistent layer, in places capped by peat, beneath the surficial wind-blown sands. If the creek deposits were younger than the induration of this sandstone, evidence of such relative age might well be found in the incorporation of derivatives from the black sandstone in the creek deposit, for, if the age and induration were considerable, the sandstone should have been of sufficient hardness to supply the two forks of the creek with pebbles and cobbles of this very easily recognizable material. Now an inspection of the freshly cleaned face of Dr. Sellards' formation No. 2—the critical formation—reveals the presence in it of many small pebbles, and not a few round "cannon balls," of this black sandstone (see Fig. 8). The latter range up to 5 inches in diameter. They are not confined to any one layer, but are scattered through No. 2 formation from top to bottom. Thus the formation in which the human bones and the extinct vertebrate remains were found also contains numerous pebbles and cobbles of black sandstone from the older formation! The stream which deposited formation No. 2 formed these pebbles of black sandstone by erosive action on stratum *b* of the upland section, through which both the north fork and the south fork of Van Valkenburg's Creek have obviously cut their stream channels. This black layer underlies apparently all the country immediately to the west of the spillway; it is a continuous, persistent layer; it was traced *in situ* to within 150 feet of where the human remains were found, and with further digging it could probably be traced still nearer. There is no other known source for the pebbles of black sandstone. *The conclusion seems, therefore, inevitable that Dr. Sellards' formation No. 2 is younger than stratum b of the upland section—the old bog surface upon which the peat accumulated.* Furthermore, it would seem to be considerably

younger, inasmuch as the old bog-covered sands had, since their formation, endured for a time sufficient to permit their upper portion to become firmly cemented by iron oxide into a fairly indurated sandstone.

INTERPRETED HISTORY OF THE BONES

As is well described in Dr. Sellards' paper, human bones were found *in situ* in formation No. 2, in close association with scattered

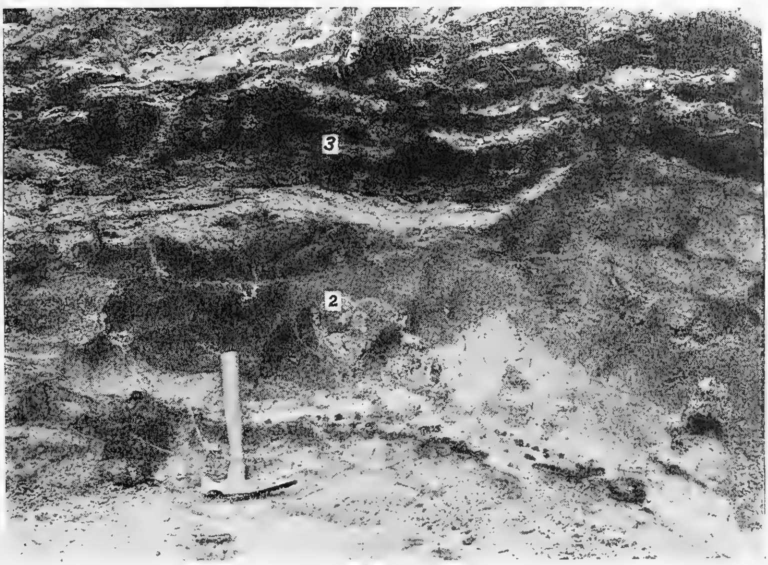


FIG. 8.—The creek section on south bank of drainage canal, about 460 feet southwest from railroad bridge. Many small pebbles (size of marbles) of black sandstone here form a band in the lower portion of formation No. 2.

bones and fragments of bones from a great variety of extinct mammals, including the Columbian elephant, mastodon, saber-tooth tiger, tapir, armadillo, sloth, bison, camel, horse, etc. This vertebrate fauna, according to Dr. O. P. Hay,[1] would seem to represent the early Pleistocene. But it should be noted again that, while the human bones make up quite a part of two skeletons, the bones of the extinct vertebrates are fragmentary and extremely scattered. This fact, that the remains of the ancient vertebrates are

[1] Personal statement on the ground.

very fragmentary, by itself suggests that they have been disturbed and transported to a greater or less extent. On the contrary, the human bones, so much less scattered as to indicate that they belong to distinct individual skeletons, imply that they have suffered much less disturbance.

The history of the bones seems to unravel as follows: For a long time during the Pleistocene there existed a marshy area of considerable extent immediately to the west of the present location of the spillway. Peat accumulated in the bog, forming layer *c* of the upland section. In the course of its growth, various animal remains of the time became incorporated. The large vertebrates were no doubt often mired, and left their bones in the bog. This is a familiar process.

During and following the accumulation of the bog and the bones, the upper portion of the sandy formation that lies beneath the peat (stratum *b*) became indurated to sandstone by the infiltration of iron oxide. At the same time it was stained black by the decomposition products of the decaying organic matter that lay over it.

With further passage of time the large land vertebrates, one after another, became extinct in the region. In the course of time also man appeared in Florida. At some time subsequent to the growth of the bog, probably as the result of a slight uplift, Van Valkenburg's Creek and its branches, or their antecedents, cut channels across the beach ridge and into the peat deposit, the two forks apparently following essentially the courses which they hold today. The drainage lines thus established cut, not only into the Pleistocene bog deposits, but into the sands beneath. With the draining of the bog and the adjacent land the movement of sand by wind action was perhaps facilitated, and the dune formation (layer *d*) which covers the old bog surface west of the spillway may have been formed during the drainage stage. It is not inconsistent, however, to suppose that it was formed before the drainage was established.

Later came the stages of partial filling of the creek channel. The first stage was occupied by the deposition of formation No. 2 of Sellards. The material for this formation was derived from the

upland section drained by the creek, not a little of it from layer *b*, as shown by the pebbles of black sandstone. The whiter portion of the sands of the stream deposit may have come from either layer *a* or from layer *d* of the upland section. To layers *b* and *c* are assigned the bones of the extinct vertebrates together with the pebbles and cobbles of black sandstone. While this deposition of formation No. 2 was in progress, the human bones are believed to

FIG. 9.—The present dry channel of Van Valkenburg's Creek just beyond the reaches of the drainage canal.

have received their first and only burial in connection with the stream deposit. The human bones should thus naturally be less scattered than the fragments of the mammals which had been shifted from their original location into the stream channel.

Following the deposition of formation No. 2 there was a period of erosion, either in the form of the ordinary scour-and-fill process of streams or as a result of ordinary subaerial denudation. A change in the stream conditions following the erosion stage caused a very heterogeneous alluvial flood-plain deposit (Sellards' formation No. 3) to be laid upon the irregular surface of formation No. 2.

Muck accumulated in alternation with layers of sand, as recurring floods from heavy tropical storms carried coarse material before them.

To this formation No. 3—just as in the case of formation No. 2—the upland bog area contributed many bones of extinct vertebrates as well as pebbles of black sandstone. At the same time human bones, pottery, and bits of flint (which does not outcrop in the region) were mingled with the flood-plain deposit, more or less directly, it would appear, as the result of human activity. There thus again came to be close assemblage of all this varied material in this formation, just as there had previously been in formation No. 2.

These conditions are interpreted as having been continued with little change (except on the human side) till the present, for pebbles of black sandstone and bones of extinct vertebrates are found *in the deposit of the present creek bed* into which formation No. 3 merges.

Two sets of evidence developed by Dr. Sellards need to be explained if we are to accept the sequence of events above outlined. Chemical analyses are cited as showing that the fossil human bones from No. 2 are quite as well mineralized as are the associated bones of the Pleistocene animals. Compared with a bone from an Indian mound near Vero, the chief difference is that the bones from No. 2 (human and other) have lost from 6 to 8 per cent of moisture and from 9 to 11 per cent of volatile matter. The loss of these easily eliminated constituents caused a proportionate increase in the percentage of calcium and phosphoric acid. But there was, in addition, an actual infiltration of silica, etc., from 0.4 to 2.9 per cent, and of iron and aluminum oxides from 0.6 to 3.5 per cent. While indicative of considerable age, it must be admitted that we do not know how rapidly bones are thus altered in sandy river beds when the adjacent sands contain abundant iron oxide.

A carapace of the turtle, *Terrapene innoxia* Hay, taken from formation No. 2 complete, though it was very fragile at the time of discovery, and the skull of a large wolf, *Canis ayersi* Sellards, are taken as evidence that the bones of the vertebrates were not transported from some other point by the creek. The turtle carapace was too fragile in the fossilized condition in which it was found to admit of stream transportation, though perhaps it could have

endured transportation before fossilization. But if the interpretation of the history of the region be as outlined above, it would not seem unreasonable to suppose (in case it be definitely established that these species have been extinct in the region since the close of the Pleistocene) that the turtle carapace and the wolf skull, and other similar parts, had been subjected to a minimum of transportation wear because originally buried in the upland formation close to the spot where they were found, and that they were carried into the channel fill by the caving of the river bank, or some similar operation involving little wear. In no case was the transportation great. The other bones found in No. 2 and No. 3, in the opinion of the writer, give as much evidence of wear and polishing as would be expected of bones that were washed only short distances (from the upland bog to the places in the channel where they were found) by the flood stages of the creek.

Formation No. 3, therefore, seems to the writer to be very recent geologically, as it is the flood-plain alluvium of the present Van Valkenburg's Creek. The age of formation No. 2 can be determined less positively. It is simply older than No. 3 and younger than the Pleistocene bog deposits that lie west of the spillway, but it is the opinion of the writer that it is much nearer in age to No. 3 than it is to the Pleistocene bog accumulation and associated deposits which originally housed the old mammalian bones.

ON REPORTED PLEISTOCENE HUMAN REMAINS AT VERO, FLORIDA

THOMAS WAYLAND VAUGHAN[1]
United States Geological Survey

Topographic relations.—Vero, a village on the Florida East Coast Railway, 228 miles south of Jacksonville, in St. Lucie County,[2] is situated on the surface of the Pensacola terrace, the lowest and youngest of the three Pleistocene terraces recognized in Florida by Matson,[3] and is about one mile west of the western shore of Indian River, between which and the Atlantic Ocean lies the great barrier beach of east Florida. The terrace plain presents the physiographic aspect of early youth, as it is almost flat and is only slightly trenched by rather indefinite drainage courses. Its surface stands between 10 and 15 feet above sea-level, except along an elevated barrier beach which lies some 600 or 700 feet west of the railroad, where the altitude may be as much as 10 to 15 feet higher. The human remains were found in a slight depression along a drainage course across the terrace surface at localities about half a mile north of Vero and between 330 and 580 feet west of the railroad, and were exposed as a result of the excavation of the Indian River Farms Company drainage canal.

Geologic relations.—Dr. Sellards has in three papers[4] presented detailed descriptions of the geologic section exposed along the

[1] Published by permission of the Director of the United States Geological Survey.

[2] See the map of State of Florida, scale 1/500,000, issued by the United States Geological Survey in 1916, and the United States Coast and Geodetic Survey Chart No. 163.

[3] "Geology and Ground Waters of Florida," *U.S. Geol. Survey, Water-Supply Paper 319*, pp. 31–35, Pl. 5, 1913.

[4] "Discovery of Fossil Human Remains in Florida in Association with Extinct Vertebrates," *Amer. Jour. Sci.*, XLII (July, 1916), 1–18; "Human Remains and Associated Fossils from the Pleistocene of Florida," *Eighth Ann. Rept. Florida Geol. Survey*, 1916, pp. 122–60, Pls. 15–31; "Human Remains from the Pleistocene of Florida," *Science*, N.S., XLIV (1916), 615–17.

canal from the Florida East Coast Railway on the east to a point about 580 feet westward from it. The stratigraphic succession may be summarized as follows: (1) The lowest observed bed is an arenaceous shell marl of Pleistocene age, the exposed thickness of which is from 2 to 6 feet. (2) Unconformably above bed No. 1 are sands, some muck, and marl, having a combined thickness ranging up to as much as 5 or 6 feet. This formation was deposited in fresh water and contains numerous species of vertebrates, which clearly indicate its Pleistocene age, and shells of about 30 species of land and fresh-water mollusks. The discovery of a locality at which so many species of extinct vertebrates are represented is of much geologic interest and importance. Within the sands human remains were found at two places, according to Dr. Sellards. (3) Overlying No. 2 is a deposit of muck, tree trunks, and other vegetable matter, in which are stringers of sand, in places containing marine shells, perhaps derived from bed No. 1 by erosion farther upstream. This deposit was accumulated in a shallow, relatively wide, channel eroded in No. 2, and has a thickness of 3 feet 6 inches in the middle of the channel, but it is much thinner on the channel sides. Whether its geologic age is Pleistocene or Recent has not been positively determined. Dr. Sellards reports human bones from near the base of this bed and from sands which lie at its base along the contact with No. 2.[1]

Criteria for determining the geologic age of the human remains.—Previous investigations having shown that human artifacts may, by many agencies, be carried below the surface of the ground and become imbedded in unconsolidated deposits, and as it is well known that human bones may have been either naturally or artificially buried, the occurrence of artifacts and human bones in association with Pleistocene fossils does not prove the Pleistocene age of man. It seems to me that the only indisputable geologic proof of the Pleistocene age of man must consist in finding a continuous undisturbed bed or layer of demonstrable Pleistocene age above the human remains (artifacts or bones) whose age is under investigation. The relative dissociation and the significance of

[1] *Eighth Ann. Rept. Florida Geol. Survey*, 1916, pp. 140–42, Pl. 17, Fig. 1, text Fig. 14.

the mineralization of the vertebrate (including the human) bones is discussed by others.

Conclusions.—As bed No. 3 may be of recent geologic age, the presence of human bones in it does not now need special consideration. With regard to the remains in bed No. 2 it will be said that as intrusion into it may have been accomplished either by natural or by artificial processes subsequent to its deposition; the presence of the human remains in it, in my opinion, is not definite proof of their Pleistocene age. However, should it be postively shown that in bed No 3 Pleistocene fossils occur *in place* above the human remains, showing that subsequent to the death of the individual represented by these remains Pleistocene species belonging to other groups of organisms lived and died, the evidence in favor of the Pleistocene age of the human remains would be conclusive. On the other hand, should it be proved that bed No. 3 is of Recent age, the human remains might be of either Pleistocene or Recent age, and it is doubtful if positive criteria for determining their age will be available unless the needed information is furnished by the human bones themselves. As the accurate determination of the geologic age of bed No. 3, especially that part of it perpendicularly above the human remains, seems to me to be critical, it is my opinion that, for the present, judgment should be suspended.

PRELIMINARY REPORT ON FINDS OF SUPPOSEDLY ANCIENT HUMAN REMAINS AT VERO, FLORIDA

ALEŠ HRDLIČKA
United States National Museum, Washington, D.C.

On the kind invitation of Dr. E. H. Sellards, state geologist of Florida, and as his guest, the writer in the latter part of October, 1916, spent four days at Vero, Florida, where his time was devoted to the study of the site from which certain human bones described by Dr. Sellards were obtained, and to a preliminary examination of the bones themselves.

Generous assistance in this work was rendered by Dr. Sellards and his associate, Mr. Gunter, as well as by the two local gentlemen most directly interested in these finds, namely, Messrs. Ayers and Weills, to whom the writer wishes to express his grateful acknowledgments.

On arriving at Vero the writer engaged workmen and with their aid made a clean exposure about 160 feet in length of the geological deposits in close proximity to the spots where the human bones had been discovered. This afforded a comprehensive and enlightening view of all the formations involved.

The two human skeletons had been found in the south bank of a recently excavated drainage canal. They occurred one in fairly close proximity to, and the other within the broad shallow bed of, a small fresh-water stream, now drained by a lateral cut from the canal. The former lay in dark and somewhat indurated sands, layer No. 2 of Sellards, the latter for the most part at the base of layer No. 3, the muck deposit of the stream bed, and "between this and the next older stratum" (Sellards). A few smaller bones which probably belonged to the second skeleton were found at about the same level and at a short distance from the rest of the remains in a small elevation of the irregularly eroded upper surface of the lower sandy layer No. 2.

The first skeleton lay at the depth of two and a half feet, the second at the depth of from two to possibly three and a half feet from the surface.[1] The first was found accidentally and taken out by Messrs. Ayers and Weills, before Dr. Sellards was notified, and before any great importance was attached to the find. The character of the deposits above it was not especially noticed, but there is no reason for supposing that they differed from those in the neighborhood, where layer No. 2 is seen to be overlain by a stratum of similar, but somewhat lighter, sandy deposits covered by a layer of marl. This marl ranges at this point from about 5 to 9 inches in thickness, and when freshly exposed is of the consistency of fresh mortar, but on exposure hardens to fairly solid rock. With some wind-blown white sand and vegetable material it forms the surface of the ground.

The second skeleton lay, according to all obtainable information, in some loose white sand and vegetable matter at the base of the muck layer, No. 3, of the stream bed. Above, up to the surface, there was only muck with irregular sandy patches. In a vertical cut these localized deposits or patches give the muck an appearance of unconnected irregular lamination, but there are no actual strata.

Skeleton No. I is that of a woman, possibly sub-adult. Skeleton No. II is that of a man, an adult of somewhat advanced years. The bones of the former, according to Mr. Ayers, who discovered and extracted them, "were all close together, the whole layer not being over one and one-half feet in width. They were not scattered at all, nor piled up." The various parts lay side by side or next to one another in about the position they would occupy in the body. The bones of skeleton No. II were dissociated, though lying within an ellipse apparently about 7 feet in length, not counting the two bones and two or three fragments found in the upper part of layer No. 2, about 6 feet away. As some of the bones of the skeleton tumbled out of the bank before the rest were removed, only a smaller portion of the parts representing the skeleton were examined

[1] In Dr. Sellards' report on the find, in the *8th Ann. Rep. of the Fla. St. Geol. Survey*, p. 142, the depth is given as 4 feet, which is evidently an error; the depth indicated in Dr. Sellards' illustrations, especially that on p. 141, is less than this.

in situ and their exact association must remain in a large measure uncertain. The skeleton lay in an inclined plane. The bones show no trace of washing or weathering. The majority of them are broken, but many of the breaks are sharp and evidently fresh,

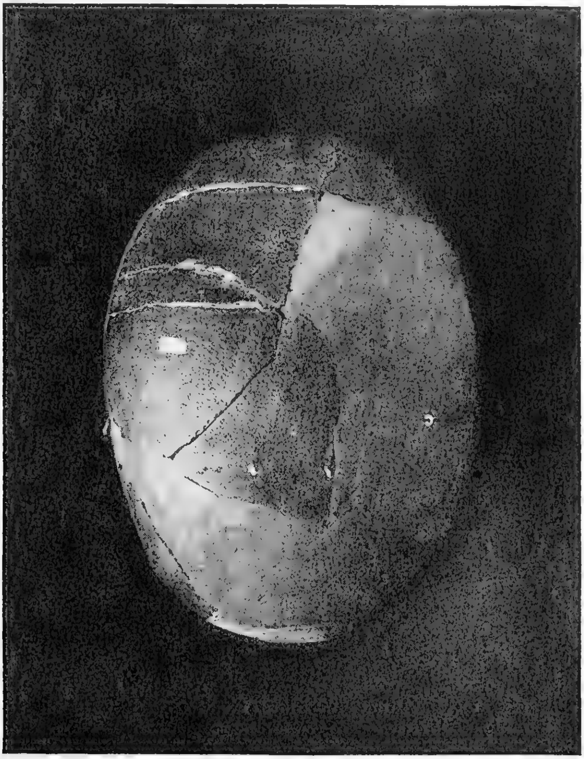


FIG. 1.—Top view of skull of skeleton No. II, from the base of muck bed (layer No. 3), south bank of the drainage canal, Vero.
c=clay; portion of frontal bleached by exposure.

dating probably from the time when parts of the skeleton were exposed in the bank or tumbled out of it.

Bones of three other individuals are found in the collection made by Dr. Sellards' party. They are a juvenile or a young adult incisor tooth from layer No. 3, in the vicinity of skeleton No. II; a tooth of a young child from stratum 3 on the opposite

or north side of the canal, and a toe bone of an adult, also from the north side of the canal.

In the muck layer on the south side, in the base of which skeleton No. II occurred, there were found, according to Dr. Sellards, "an abundance of pottery, many bone implements, arrowheads, and other small flints."

Speaking further on this point, Dr. Sellards says (p. 143):

> A considerable amount of broken pottery is found in this horizon, particularly at the locality on the south bank 450 to 475 feet [bones of skeleton No. II were located from about 460 to 473 feet] west of the bridge. Bone implements are also numerous and were made evidently to serve a diversity of purposes. Well-worked flint arrowheads are found also, as well as occasional spalls from the manufacture of flints. The pottery, flints, and bone implements, however, are not confined to this locality on the south bank, but are found also in the same horizon on the opposite side of the canal.

A few small flints and two bone implements were found in stratum No. 2 (p. 140). The flint of the several chips and implements, which must have been brought from a considerable distance, is quite similar in the two deposits; and the bone implements of the two sections seem identical in character.

The portion of the muck of the stream bed on the south side of the canal nearest where the bones of skeleton No. II were discovered was found to be a moderately compressed, wet mass of leaves and other detritus. Many of the leaves, though generally imperfect, were still so pliable that they could be unfolded and straightened out, and were still fairly elastic. In this muck are trunks of trees and branches or roots, partly in a fair state of preservation, partly softened or rotted.

During the clearing work carried on by the writer, fossil animal bones were found to be fairly numerous in layer No. 2, beneath the muck of the stream bed. There were uncovered possibly several hundred specimens of this nature. They were isolated, small and large fragments, some apparently waterworn, with a few individual bones, and parts of turtle shells. The largest individual specimen was the tooth of a large herbivore. Two or three fragmentary fossilized bones were also obtained from a sandy band in the lowest portion of the muck deposit.

The foregoing comprises in brief the writer's personal observations at Vero, with the exception of those on the human bones themselves. After a careful weighing of the facts, both on the spot and afterward, he regrets that he cannot agree with the conclusions reached by Dr. Sellards as to their antiquity. It seems to him that there is another possible and more likely explanation of their occurrence in the deposits than that which would make

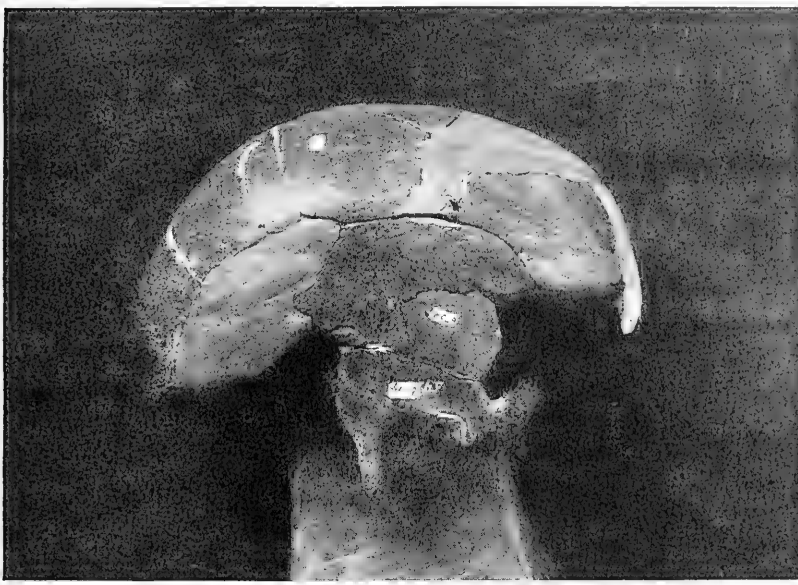


FIG. 2.—Right side of skull belonging to skeleton II (frontal bone, light from exposure, on the right, occiput on the left).

them contemporaneous with the various fossil animals the remains of which are found in the same layers, and some of which may date from the middle or even early Pleistocene.

A relatively small amount of work brought to light the remains of five human individuals—a small child, an adolescent or young adult, a young woman, and two adult men. In the vicinity of these occurred a quantity of pottery fragments, resembling closely the usual Florida variety, bone implements, and stone implements with chips, and all in proximity to, or in, the bed of a

fresh-water stream. To the anthropologist the various finds strongly suggest an ordinary "station," or inhabited site, with burials of probably prehistoric, but not necessarily very ancient, man, whose culture horizon corresponded to that of the ordinary American aborigines of the eastern and southeastern states.

The two human skeletons occurred at nearly the same depth, which would be about that of a common Indian burial. The bones of the one were in close and natural association; those of the other, buried in or just below the unstable muck, though dissociated, yet remained fairly well aggregated, preserving some original relations. The condition of these remains, contrasted with that of the animal fossils with which they were associated, is instructive. The number of individual fossil animal specimens recovered by the local explorers, Dr. Sellard's party, and the visiting scientists would doubtless reach several thousands, and they were with a few exceptions isolated bones or teeth or mere fragments, many of which were hardly worth collecting.

The occurrence of isolated fossil animal bones or fragments in contact with, or even above, the human skeleton would have no significance. In digging a grave the earth thrown out might well contain fossils even of considerable size, which, after the body was introduced, would be thrown in about or above it.

The apparently undisturbed condition of the partial and irregular sandy layers which occur in the muck where skeleton No. II was discovered could hardly be regarded as sufficient proof that the bones were not introduced from above. The muck and sand thrown in over a body would tend in the course of time so completely to assume the appearance and characteristics of the original deposits that distinction between the two would be quite impossible. Very good examples of restratification and striation are seen at Vero in the accumulations thrown out from the canal by the dredges.

The human bones are considerably "fossilized." But they are not fossilized equally in the two skeletons,[1] nor even in the different parts of one and the same skeleton. The mineralization also is not

[1] The considerably smaller female astragalus weighs 26 grams, the much larger male bone but 20.7 grams.

quite like that of the animal bones from the same deposits, though the approach, especially in parts of skeleton No. II, is close. Even if they were identical, however, in this respect, the fact could not be taken as a gauge of their contemporaneity with the animal bones. Mineralization is a chemical-mechanical process, which runs its course slowly or rapidly, according to circumstances. Under similar conditions two bones, ages apart, would "fossilize" in a similar manner; but one of the bones would have completed the process long before the other. The writer has dealt with this subject in his report on "Ancient Man in North and South America."[1] In the corresponding work on North America will also be found described examples of human bones, petrified in different ways, from the west coast of Florida. One of the skeletons from that locality, in the possession of the United States National Museum, is apparently even more completely petrified than the human bones from Vero. In Florida, mineralization of bones or their inclusion in geological deposits has little chronological significance.

The "fresh-water marl" that covers the deposits in the locality of skeleton No. I is not found over the muck layer, or layer No. 3, from which came skeleton No. II, but the point is immaterial. The layer, except where exposed, is not or is but partly consolidated; and even if it were solid it would have little bearing on the antiquity of whatever may lie underneath. The writer found a very good demonstration of this after he left Vero, on the Demere Key, off Fort Myers on the west coast of Florida, and not very far south of the latitude of Vero. He found there a low sand burial mound the entire surface of which, consisting of sand, organic matter and shells, materials gathered from the vicinity of the mound and from the seashore, was consolidated to the depth of from four to sixteen inches to such a degree that in places it was almost impossible to penetrate it with a mattock. This "rock" included numerous human bones, even skulls, a series of which is now in the National Museum. Its age is possibly post-Columbian, for there were found on the Key fragments of Spanish pottery and glass, while burial sand mounds on neighboring keys yielded glass beads.

[1] *Bureau American Ethnology Bulls. 33 and 52.*

In considering these problems the anthropological characteristics of the bones themselves deserve serious consideration. They now lie before the writer, and he has not found as yet a single feature in which they would not agree with recent, more especially Indian, bones. The juvenile or young adult incisor tooth presents in a typical way the highly specialized characteristic form of the Indian middle upper incisor; what there is of the lower jaw is wholly of modern form; the skull of skeleton No. II by its lack of thickness, good size, and subdued supraorbital ridges is actually of a type superior to that of a large majority of the Florida Indians; and the shape and dimensions of the other bones are those of a man of the present day. There is nothing which would remind the anthropologist of early man.

In conclusion the writer wishes to submit that besides all the foregoing considerations there are broader anthropological and archaeological problems which should receive due attention in all cases of this nature. They are both cultural and anthropological, and their discussion must be reserved for the detailed report. It may, however, be here briefly pointed out that an advanced state of culture such as that shown by the pottery, bone implements, and worked stone (brought from a considerable distance) implies a numerous population, spread over large areas, acquainted thoroughly with fire, with cooking food, and with all the usual primitive arts. Such a population would surely have left many tangible traces of their presence on the Continent, some of which at least would by this time have been discovered.

It is the opinion of the writer, as the result of his investigations, that the human bones found at Vero may well be prehistoric, and date from the early part of the occupation of the Florida peninsula by the Indians; but that no proof is furnished by the circumstances of the find, or by the human bones themselves, which would relegate the latter to an antiquity comparable with that of the fossil remains with which they are associated.

ADDENDUM

While at Vero the writer obtained from Mr. Weills 20 fragments of pottery recovered from the Vero deposits. In addition to this, two fragments were obtained from the sand mound on the

Indian River. This pottery was submitted for examination to Professor Holmes, and his report follows:

December 1, 1916.

Dear Doctor Hrdlička:

I have examined with great care the pottery fragments obtained from the site of the discovery of human remains associated with Pleistocene deposits near Vero, Florida. They represent moderately small, undecorated vessels, apparently simple bowls such as were in common use among the Indian tribes of Florida. Compared with corresponding plain vessel fragments from Florida sand mounds and from occupied sites generally, no significant distinctions can be made; in material, thickness of walls, finish of rim, surface finish, color, state of preservation, and size and shape of vessels represented, all are identical. There thus appears not the least ground in the evidence of the specimens themselves for the assumption that the Vero pottery pertains to any other people than the mound-building Indian tribes of Florida or to any other than Columbian and immediately pre-Columbian time.

Sincerely yours,

W. H. Holmes

Head Curator, Department of Anthropology

THE QUATERNARY DEPOSITS AT VERO, FLORIDA, AND THE VERTEBRATE REMAINS CONTAINED THEREIN

OLIVER P. HAY
Research Associate, Carnegie Institution of Washington.

I arrived at Vero on the evening of October 25 and left there on October 31. Having examined with some care the geological situation and having studied somewhat the vertebrate fossils found in the strata designated by Dr. Sellards as No. 2 and No. 3, I reach the following conclusions:

1. *Stratum No. 2 was in general laid down during the Pleistocene.*—It seems hardly necessary to present arguments to sustain this conclusion, for it is hardly probable that anyone will call it in question. It is possible that some parts of the stratum were afterward re-worked by the streamlet which flowed over it, but this was accomplished during Pleistocene times.

2. *The vertebrate fauna of No. 2 belongs to the Pleistocene, and most of it is there by primary inclusion.*—No place was discovered from which the included bones and teeth might have been washed in, nor do they in general have the appearance of transported fossils. These bony remains are in what may be regarded as a normal condition; as when, in a little valley furnishing food and drink and shade, herbivorous and carnivorous species had resorted and perished there for thousands of years. In a normal way their bones have almost all fallen into dust. Some, buried under somewhat favorable conditions, endured longer, but softened and were trampled into fragments by succeeding generations of elephants, mastodons, horses, bisons, huge ground sloths, and smaller forms. Only the most favored and protected bones and teeth have endured to the present, mostly scattered, but sometimes remaining associated with others of the same skeleton.

3. *At least the lower part of No. 3 is also of Pleistocene age.*—This deposit is somewhat more difficult to work for fossils, but it

has furnished almost all the forms that are found in No. 2. It is not improbable that some bones and teeth were redeposited from the lower stratum, but not, I think, any considerable or essential portion of them.

a) Considering the relatively small amount of erosion which No. 2 suffered from the stream which laid down the muck bed, there are too many fossils in the latter to permit the conclusion that any great number of them came from the older deposit. The lowest layers of muck early formed a blanket which protected the sands of No. 2 from further disturbance.

b) The state of preservation of the fossils of No. 3 does not indicate that they were redeposited from No. 2. They are not more broken and waterworn than those of No. 2.

c) There are some extinct species in No. 3 whose remains must lie where originally buried. The box-tortoise *Terrapene innoxia* is found in both strata. Although the bones of the carapace are usually co-ossified into one mass, this shell is so thin and brittle that it would certainly have fallen into pieces on being rolled along a stream bed. It is even now extremely difficult to unearth a shell without breaking it. Yet one whole carapace and large portions of others have been secured from No. 3. From this muck bed there come seven bones of one individual of an extinct snapping tortoise, probably *Chelydra sculpta*. The shell of this animal, like that of our living species, is thin and loosely articulated. On maceration the bones separate easily. Had the seven bones referred to been buried originally in No. 2, they would, on being washed out, have been scattered like autumn leaves.

d) In No. 3 there is a deer of the genus *Odocoileus* which is smaller than the one found in No. 2.[1] From No. 3 Dr. Sellards has sent me a fifth cervical vertebra which shows that this deer is very distinct from the existing Virginia deer and still farther removed from the mule deer. The fox referred with doubt by Dr. Sellards to the red fox is certainly an undescribed species, having had a heavier lower jaw than that of the red fox. A femur from No. 3 probably belongs to the same species. It is larger, straighter, and more flattened than that of the red fox.

[1] Sellards, *8th Ann. Rep. Fla. Geol. Surv.* p. 149.

In short, there are so many well-preserved extinct vertebrates in No. 3 that it must be referred to the Pleistocene; and the study of the collections adds continually to the number.

4. *A few words only about the human bones.*—I consider now only those found at the locality illustrated by Sellards' Text-Fig. 6 and his Plate 16 and Plate 17, Fig. 2. Had no human bones been found there the following explanation would, I think, hardly be questioned. No. 2, consisting mostly of sand, had been deposited, leaving traces of horizontal stratification. At a later time the swollen streamlet cut down through it to the underlying marl. About four feet away at the same time it cut down nearly to the marl. The two currents left a ridge of undisturbed sand which contained some bones. As the currents lost their force, sand began to be deposited on the sides and summit of the ridge. Had there been any considerable interval, this ridge of sand would have been flattened down and disturbed in various ways. Before the freshet spent itself a mass of vegetation was swept down and deposited, mostly in the channels but partly on the ridge, thus sealing it in until our day. As to the human bones found lying on the slope of No. 2, a reasonable explanation is that they had previously been scattered and inclosed in its sands and then laid bare by the freshet. Their condition of fossilization is the same as that of the animal bones found near by, and their broken condition indicates that they had suffered from the trampling of animals, as those other bones had.

5. *The age of stratum No. 2 and of at least the lower part of No. 3 is not later than middle Pleistocene.*—The fauna afforded by the deposits in question is essentially that which is found in the Aftonian interglacial beds in Iowa and in the Equus beds of the Plains. From the latter it may be followed into Texas, thence eastward into Florida and South Carolina. Of this fauna two species of elephants, the common mastodon, *Megalonyx*, and the giant beaver, continued on until after the Wisconsin glacial stage. Other species, the saber-tooth tigers, *Equus complicatus*, the tapirs, most of the extinct bisons, and *Mylodon* probably disappeared before the Wisconsin. In the earlier Pleistocene deposits only are found *Elephas imperator*, camels, several species of horses, and many edentates. At Vero have been found three species of horses, at least four

edentates (including *Mylodon*), and a camel. *Chlamytherium* was originally found on Peace Creek in deposits which were then supposed to be Pliocene. In the same deposits was found a jaw containing a tooth of an elephant which is quite likely *E. imperator*. This species has not yet been found in No. 2 at Vero, but about three miles west of the place Sellards found a lower jaw which belongs probably to this species. It is known from Dallas County, Alabama, and from Charleston, South Carolina. The writer regards it and camel remains as particularly indicative of the Aftonian fauna.

It is possible that this fauna continued on for another stage or two without great change, but by the time of the Illinoian drift it had become essentially modified.

6. *The human bones appear to be of Pleistocene age.*—At present I perceive no other reason for doubting this than that their presence in No. 2 and No. 3 contravenes our present ideas regarding the history of the human race.

ARCHAEOLOGICAL EVIDENCES OF MAN'S ANTIQUITY AT VERO, FLORIDA

GEORGE GRANT MACCURDY
Yale University

The apparent association of human remains and artifacts with fossil animal remains in Pleistocene deposits is always and everywhere sufficient to challenge the attention of scientists. This is especially true of the New World, where Pleistocene man has not yet won a place in the prehistoric hall of fame; hence the wide interest taken in the announcement by Dr. E. H. Sellards,[1] state geologist of Florida, that he and his colleagues had found such an association at Vero, Florida.

As one of several invited to investigate the circumstances of the find on the spot, the writer obtained leave of absence from Yale University for this purpose, and visited the Vero site during the week of October 23–29 as the guest of Dr. Sellards. To him and to his assistant, Mr. H. Gunter, as well as to his local associates, Messrs. Frank Ayers and Isaac M. Weills, grateful acknowledgments are due for facilities so generously extended. The writer's visit approximately coincided with those of Dr. Rollin T. Chamberlin of Chicago and Drs. O. P. Hay, A. Hrdlička, and T. Wayland Vaughan of Washington, D.C. The headquarters of the party were at the site itself, one-half mile north of the village of Vero, and easily reached by the highway that parallels the railroad tracks.

The drainage canal which cuts through the site is of itself sufficient proof of the flatness of the country. The human remains and artifacts and the fossil animal remains were all found at the junction of two lateral valleys, which united to form the trunk of a wider valley; in this valley until recently a stream followed an "ill-defined, anastomosing, and frequently changing channel." At

[1] *Amer. Jour. Sci.*, XLII (July, 1916); *Eighth Ann. Rep. Fla. State Geol. Survey*, pp. 121–60, 1916; *Science*, N.S., XLIV (October 27, 1916).

this junction the canal enters from the west the main-stream valley, which it follows for some 800 feet.

Along both banks of the canal Dr. Sellards had prepared sections for the inspection of the party. One of these sections was extended by Dr. Hrdlička, who also opened up a new section along the east bank of the tributary canal that follows the course of the lateral valley entering from the south. Additional animal remains were found daily during the stay of the party, especially in the middle one of the three strata described by Dr. Sellards. As to the correctness of his interpretation of the stratigraphic section there would seem to be little doubt. It remains to be seen whether all his conclusions can stand the test with equal success.

Dr. Sellards had brought with him from Tallahassee human remains found to date in stratum No. 2 and along the contact line between it and stratum No. 3, also certain flint chips, bone implements, the tip of a proboscidian tusk, and a fragment of a bird bone —the last two with markings which he believed to have been made by tools. These were all carefully studied by the writer while he was at Vero. Later the human bones were sent to Dr. Hrdlička at the National Museum and will be the subject of his contribution. From a study of them at Vero before the broken parts were assembled, and without material at hand for comparison, the writer agrees with Dr. Hrdlička that they are in no way different from Indian skeletal remains found in the sand mounds of Florida. In the writer's opinion the markings on the tip of the proboscidian tusk and on the fragment of bird bone, both from stratum No. 2, are not the work of man.

A consignment including flint chips and implements, bone implements, and an ornament and potsherds were sent to New Haven after the writer's return. The sherds and some of the other objects are from stratum No. 3. Some of these specimens were figured by Dr. Sellards; certain of the figures which seemed to be inadequate in Sellards' work are reproduced herewith.

The flint spall, No. 6964 (Sellards' Text-Fig. 11), was found in stratum No. 2, in the south bank, 460 feet west of the railroad bridge and 3 feet from certain bones of human skeleton No. II (Fig. 1). Another and smaller spall of identical material, which might well

have been chipped from the same parent block, was, according to Sellards, found in the south bank 460 feet west of the bridge, but in stratum No. 3 (Fig. 2). That of these two chips of like material and so near each other in respect to horizontal displacement one should have been found in stratum No. 3 and the other in stratum No. 2 is significant. The question arises whether both might not have been originally in stratum No. 3, one having worked its way down into No. 2 by the aid of growing roots or burrowing animals. While Dr. Sellards does not recall having seen any roots reaching into stratum No. 2 where the spall reproduced in Fig. 1 was found, he admits that roots do penetrate this stratum in places, notably a

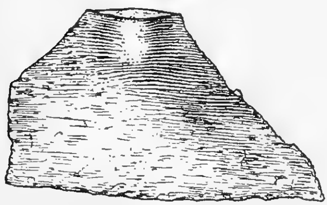


FIG. 1

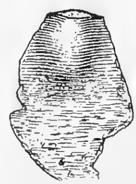


FIG. 2

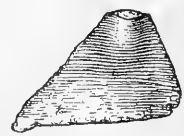


FIG. 3

FIGS. 1–3.—(1) Flint spall from stratum No. 2, south bank, 460 feet west of the bridge and near human bones; (2) flint spall of identical material from stratum No. 3, south bank, 460 feet west of the bridge, from siftings; (3) flint spall from stratum No. 2, south bank, 460 feet west of the bridge, from siftings ($\frac{1}{1}$). Nos. 6964, 7072, and 7049.

little farther west where flint No. 7055 (not herein figured) was found.

These spalls were never retouched or utilized. Each has what the French call a *plan de frappe* ("plane of percussion") and a well-marked bulb of percussion. The inner or conchoidal surface is fresh and the edges are unworn. They were evidently chipped from the parent block not far from where they were found. At one time the presence of a bulb of percussion was looked upon as a sure sign of human agency. Certain rare examples from the base of the Eocene at Belle-Assise, Clermont (Oise), and from the Oligocene at Boncelles, Belgium, are proof that the bulb is not an infallible sign. By accidentally letting one flint fall upon another, the writer has on one occasion unintentionally caused the production of a bulb of percussion. It is, however, quite logical to assume that the vast

majority of chips with bulbs that occur in Pleistocene and later deposits have been produced intentionally, especially when associated with human skeletal remains or with undoubted artifacts. This is doubly true at Vero, because the source of the flint is the Ocala or the Tampa formation a hundred miles to the northwest of Vero. The cores from which the chips were struck could not well have been transported that distance over so flat a country except through human agency.

The small flint chip reproduced in Fig. 3, and thought by Sellards (his Text-Figs. 7 and 8) to be an implement, is likewise only a chip or spall with its plane of percussion and bulb of percussion. The multiple facets on its back or outer surface are due to the fact that it was an inner instead of a superficial chip. It also is from the south bank 460 feet west of the bridge, hence from near skeleton No. II and the other two spalls here reproduced. While obtained from siftings, it is believed by Dr. Sellards to have come from stratum No. 2. In a recent letter he emphasizes the fact that "up to the present the number of spalls taken from stratum No. 2 is in excess of the number taken from stratum No. 3, notwithstanding that rather more material from No. 3 has been handled, and fully as much material from that stratum has been passed through the sieve as from stratum No. 2." This fact, however, would not seem to have any very direct bearing on the question whether or not flints from stratum No. 3 had worked their way down into stratum No. 2.

A typical arrowhead of flint with barbs and stem, the latter however broken off, came from the contact line between strata No. 2 and No. 3 in the south bank 470 feet west of the bridge (Sellards' Fig. 1, Pl. 21).

For the sake of comparison bone implements from strata No. 2 and No. 3 are reproduced in Figs. 4–6. Fig. 4 is a typical point from stratum No. 3, south bank, one of several from 450 to 470 feet west of the bridge. The fragment of a similar point, obtained in siftings from stratum No. 2, south bank, 462 feet west of the bridge, is shown in Fig. 5. Another and nearly complete point, obtained in siftings from stratum No. 2, south bank, 480 feet west of the bridge, differs from the other two only in size (Fig. 6).

So far as the writer is aware no potsherds have as yet been reported from stratum No. 2, although they occur somewhat plentifully in stratum No. 3. Of the dozen sherds sent to New Haven every one is more or less waterworn. When subjected to stream action, these sherds would show the effects of wear quicker than would the bones, flints, and bone implements. The pottery is of fairly uniform quality, the paste being neither crude nor fine. It is black to brown in color and the walls are of medium thickness. Judging from these twelve sherds, the ware was unpainted and undecorated. Of the three rim fragments, two are from bowls of

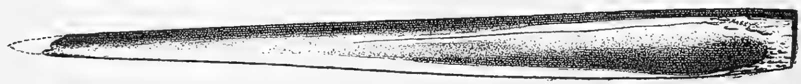


FIG. 4

FIG. 5

FIG. 6

FIGS. 4–6.—(4) Bone point from stratum No. 3, south bank, 450–70 feet west of bridge; (5) fragment of bone point from siftings of stratum No. 2, south bank, 462 feet west of the bridge; (6) bone point from siftings of stratum No. 2, south bank, 480 feet west of the bridge ($\frac{2}{3}$). Nos. 6912, 6963, 6981.

medium size, the third, somewhat thicker, is from a medium-sized bowl with slightly incurved rim. All these rims are plain but carefully finished. The smoke stains and accumulated soot indicate that these were culinary vessels. It should be recalled that the sherds, flints, and bone implements of stratum No. 3 are found in the north as well as the south bank of the canal at the junction of the two lateral valleys previously mentioned. None of these differ from similar antiquities found on the surface or in Florida mounds.

To summarize the archaeological evidences of man's antiquity at Vero, one can say that the pottery, bone implements, including fishhooks, bone heads, and flint arrowheads from stratum No. 3 and from the surface of contact between it and the stratum below,

all point to a period that might well have continued down to the close of the prehistoric period in Florida. This is also true of the human skeletal remains from the third stratum. On the other hand, of the 25 mammalian species from the second stratum as listed by Dr. Sellards, ten, including *Elephas columbi*, *Mammut americanum*, *Equus leidyi?*, and *Tapirus haysii?*, recur in stratum No. 3. Assuming that the stratigraphy is not misleading, the conclusion is either that this particular phase of the Neolithic period in America dates back farther than many had supposed, or else that certain fossil mammals continued to live on in Florida until a comparatively recent date.

The chief interest centers in the second stratum. From it no undoubted stone implements have thus far been reported. Although probably produced through human agency, the flint spalls from this deposit do not differ from those in the deposit above, in one case there being absolute identity of material. While a greater number of bone objects have been found in the third deposit than in the second, bone points of the same type occur in both; neither do these seem to differ as to their chemical state. Potsherds, fairly frequent in stratum No. 3, have not yet been reported from the stratum below. Of the human skeletal remains there does not seem to be any appreciable differentiation between those from the second and those from the third stratum.

There are to be noted then the absence of well-defined stone artifacts and of pottery from the second deposit; the presence of both in the third; the similarity of the flint chips from the two deposits; the similarity of the bone points in both deposits; and the greater number and variety of bone artifacts including ornaments in the third deposit. But for the similarity of the flint chips and the bone points the cultural evidence is very much as one might have been led to expect, assuming of course that the stratigraphy is unmixed and that all specimens have been found *in situ*. On the other hand, in the absence of stratigraphy as a guide, of all the human and cultural remains reported from stratum No. 2 none would seem out of place in stratum No. 3.

It will be recalled that one flint spall (see Fig. 3) referred to the second stratum was from siftings; and that the two bone points

(see Figs. 5 and 6) referred to the same stratum are likewise from siftings. Even if these were eliminated, there would still remain as stratigraphically troublesome elements the two flint chips (see Figs. 1 and 2). The presence of plant stems, acorn cups, and pieces of wood in the second stratum, although by no means so abundant as in the third stratum, nevertheless give to it an aspect of comparative newness. Some of the leaves in the muck at the base of the third stratum look as if they might have been buried only a few years ago.

From observations made on the spot and from a study of specimens submitted, the writer is of the opinion that for the most part the human skeletal remains, flint chips, and artifacts probably found their way to this meeting-place of waters through the same agencies as did the various animal and plant remains, and that there has been more or less dovetailing of the two deposits, because of the peculiar location of the site at the junction of two streams coming from opposite directions. If these premises be true, it would be hazardous to attribute any great antiquity to even the oldest human and cultural remains from Vero. It would be more logical to assume that some of the extinct forms found in the second stratum are perhaps derived from an older deposit; that others lived on in that southern clime longer than has hitherto been supposed, and that the presence of the Indian hunter had much to do with the final ringing down of the curtain on the drama of their ultimate extinction.

SUGGESTIONS FOR A QUANTITATIVE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS

ALBERT JOHANNSEN
University of Chicago

It is with considerable hesitation that the writer introduces a new classification of igneous rocks. He knows that he who adds a single term to an already overburdened vocabulary is looked upon with disfavor, while he who brings in many has hearty objurgations heaped upon him; yet he hopes, as others who have gone this way before him have hoped, by fixing definite boundary lines beyond which the different families cannot pass, to eliminate the multiplication of names for rocks which differ in no essential particulars from previously described types.

It is being recognized, more and more, that there is need for three classifications of igneous rocks. Of these, one must be for field use[1] and megascopic. Another must be chemical, after the manner of the systems of Osann[2] and C.I.P.W.[3] The third must be mineralogical. The old classifications of Rosenbusch and Zirkel are more or less mineralogical, it is true, and are not to be discarded lightly, but they fail especially in their lack of the quantitative element. Furthermore, they are neither purely mineralogical, purely chemical, nor purely geological. For example, certain dike-rocks are classified by Rosenbusch, on the basis of their field associations with nephelite-syenites, essexites, etc., as rocks of the alkali series, and to them he gives specific names, yet they are mineralogically and chemically identical with normal rocks of the alkali-lime series. He depends in part, therefore, on field associations

[1] Field classifications are given by Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks* (Chicago, 1903), p. 180; L. V. Pirsson, *Rocks and Rock Minerals* (New York, 1908), p. 202; Albert Johannsen, "Petrographic Terms for Field Use," *Jour. Geol.*, XIX (1911), 317–22. A revised form of the latter will appear shortly.

[2] A. Osann, *Tschermak's Mitteilungen*, XIX, XX, XXI, XXII (1899–1903).

[3] Cross, Iddings, Pirsson, and Washington, *op. cit.*

for classification. Elsewhere he uses chemical data to classify rocks which he defines in mineralogical terms; for example, the SiO_2 percentage must lie between certain limits, or the sum of the alkalies must be less than the alumina, etc.

Another objection to the present system of classification is the fact that rock terms have been used loosely or with different meanings. Thus dolerite, originally applied to a coarse basalt, has been used for any dark rock, and in England is used for rocks which we call diabases. The term diabase in the United States means a dike-rock with an ophitic texture, yet it was originally used for Paleozoic basalts and is still so used in various countries. Basalt has been applied to plagioclase rocks with augite and olivine irrespective of the kind of feldspar, to labradorite-pyribole[1] rocks with or without olivine, to the darker labradorite-pyribole rocks, to post-Tertiary extrusives of gabbroic magma, etc.

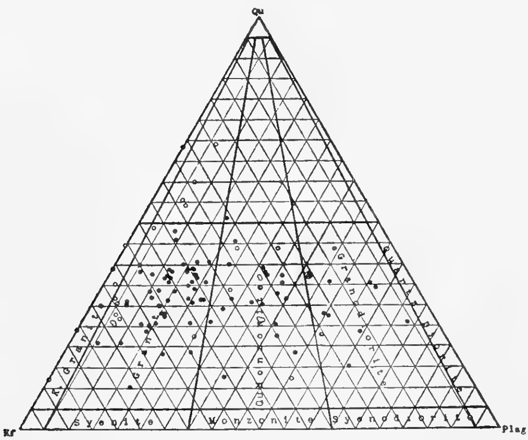


FIG. 1.—One hundred and nine so-called "granites." Open circles are rocks of Class 1, and dark circles rocks of Class 2. The double circle is the mean of Daly's granites recomputed into the probable modal minerals.

The loose usage of terms by different writers with respect to the mineralogical compositions of rocks is well brought out by Figs. 1 and 2, in which the three corners of the triangles represent respectively quartz, potash-feldspar, and plagioclase. In Fig. 1 are plotted 109 so-called "granites," taken, not from old descriptions, but from comparatively recent ones in which the actual mineral compositions were determined by the Rosiwal method or by careful estimation by the various writers themselves. In a few cases the rocks were doubtless named on the basis of their

[1] A general term for the members of the pyroxene and amphibole groups (Albert Johannsen, *op. cit.*).

chemical compositions, but in most cases their chemical compositions are as far from true granites as are their mineral compositions. The figure shows that there are actually 6 potash-granites (one of them quartz-rich), 63 normal granites (4 of them quartz-rich), 29 quartz-monzonites (1 of them quartz-rich), and 11 granodiorites. Fig. 2 represents 30 so-called "syenites." There are 2 potash-syenites, 3 normal syenites, 14 normal granites, 3 monzonites, 7 quartz-monzonites, and 1 granodiorite.

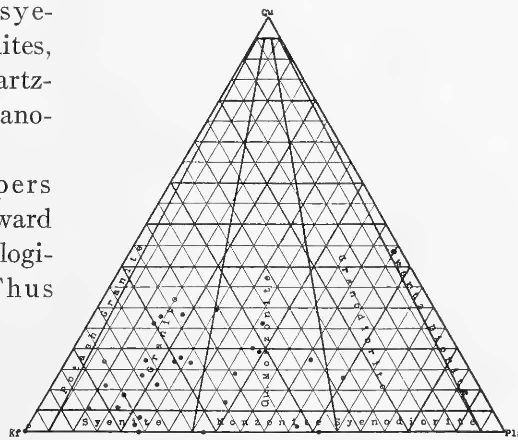


FIG. 2.—Thirty so-called "syenites"

Many recent papers show the tendency toward a quantitative mineralogical classification. Thus Brögger proposed fairly definite boundaries for monzonite and quartz-monzonite. From the latter Lindgren separated granodiorite, and established limits so clearly that almost all rocks described as granodiorites are actually such. But covering a wider field are later papers by Iddings[1] and Lincoln.[2] Each of these writers proposed a definite classification, and more recently Shand[3] suggested subdividing rocks according to their percentages of light and dark constituents. To the writer, none of these classifications appears so satisfactory as that which he has presented to his students, with various modifications, during the past seven years. The system was first thought out in the summer of 1909, and even so long ago as the summer of 1910 the writer prepared plaster models of tetrahedrons, cut into subdivisions essentially as shown here. Owing to press of other work and lack of

[1] Joseph P. Iddings, *Igneous Rocks* (New York, 1913), Vol. II.

[2] Francis Church Lincoln, "The Quantitative Mineralogical Classification of Gradational Rocks," *Econ. Geol.*, VIII (1913), 551–64.

[3] S. J. Shand, "A Recording Micrometer for Geometrical Rock Analysis," *Jour. Geol.*, XXIV (1916), 404.

sufficient data in the literature as to the modes of rocks, the publication was delayed. In the present paper the writer presents the system in a tentative form, hoping to receive from other petrographers expressions of opinion and suggestions for modifications. Later he hopes to show the relationships, both mineralogical and chemical, existing between the rocks falling into the various groups.

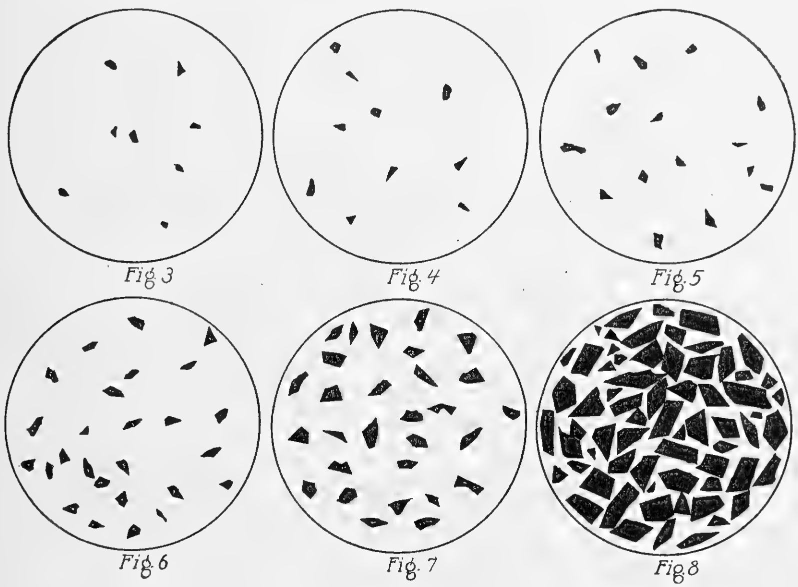
The system here proposed is strictly mineralogical, quantitative, and modal, and is directly applicable to all plutonites and to practically all extrusives. The writer's objections to the percentage values set by various other authors will be given below. Apparently the dividing lines have previously been arbitrarily selected, and no attempts have been made to gather published data with respect to the modes of rocks. There is, in fact, a surprising lack of such data, the writer having been able to find published reports of less than 600 quantitatively determined rocks.

If the reader has ever attempted to find, from the average report, the relationship existing between a newly described rock and the older types, he will in many cases have found it impossible. This is clearly shown by the fact that Rosenbusch himself, by the misinterpretation of descriptions, has misplaced rocks, grouping them with totally unrelated types. If the reader will turn at random to almost any petrographic report,[1] and will read a description and then attempt to picture to himself the rock described, in most cases he will find that owing to lack of quantitative data no idea as to its appearance can be obtained.

A name should convey an idea as to the character and appearance of a rock, and it should not be necessary, as it now unfortunately is, for one to read the description of a rock to know what a writer means. So far as the name itself is concerned, it is of slight importance, provided the texture is described and accurate quantitative details of the average rock are given. But without quantitative details serious errors may arise. Thus in a recent petrographic report a rock was said to contain orthoclase, andesine, quartz,

[1] The writer is guilty of having written indefinite descriptions himself. As an exception to the general rule of poorly written and indefinite reports, he likes to refer his students to Dr. H. S. Washington's "Roman Comagmatic Region," *Carnegie Publication No. 57*. Here there is never the least doubt as to the mineralogical composition and appearance of a rock.

biotite, and hornblende, and was called a syenite. One naturally would suppose from the name that andesine and quartz were of subordinate importance, yet an examination of many thin sections showed 20 per cent quartz and 30 per cent each of orthoclase and andesine, a rock which is a quartz-monzonite BRÖGGER. One rock found to be thus incorrectly named raises doubts as to the accuracy of the determinations of all other rocks in the same report.



FIGS. 3–8.—Various proportions of dark minerals in a rock

During the past few years the writer has required his students, in their rock descriptions, to give the percentages of the different constituents,[1] and he has invariably found that the estimates of the less abundant minerals, such as the dark constituents in leucocratic rocks or the light constituents in those that are melanocratic, are entirely too high, and that the first summation of all the constituents runs between 80 and 95 per cent. The reader may test for himself, before reading farther, his ability to estimate percentages by examining Figs. 3 to 8, which were made by pasting

[1] For a specimen card showing percentages see Albert Johannsen, *A Manual of Petrographic Methods* (New York, 1914), p. 614.

into circles of known size irregular fragments cut from pieces of black paper which bore definite ratios to the circles.[1] Of course, if one has often measured constituents by the Rosiwal method his estimates are likely to be fairly good.

The system here presented is not intended as a substitute for any chemical system. But, as so well expressed by Clarke, "Even if it [the C.I.P.W. system] should be finally adopted by all petrologists, some form of classification like that now in vogue would have to be retained with it. Good analyses cannot be obtained for every rock which the geologist is called upon to determine, and in many cases he must be content with the results of a microscopic examination."[2] And it is also true that for rocks which show considerable decomposition the microscopic method is far more likely to give good results than the chemical.

As an objection to a quantitative mineralogical system, such as is here proposed, it will be said that it is not always possible to determine the exact composition of rocks with a glassy base or extrusive rocks of the alkali series. But the percentage of indeterminable rocks is comparatively small, and for these there still remain, if necessary, chemical methods for determining the composition of the base. Most glassy rocks are leucocratic, and a recalculation into the minerals which would have crystallized had the conditions been right is easy. Since the majority of these glassy rocks are rhyolitic, one is no worse off in adopting a quantitative classification than at the present time, when they are called rhyolites from microscopic examination. In such cases it would not be objectionable to make use of tentative names which could be revised after chemical analyses have been made. In a later paper the author hopes to present a method for determining quantitatively even these rocks with very little difficulty. Certainly 95 per cent of fresh igneous rocks can be classified microscopically. When rocks are completely decomposed, no determinative system, chemical or mineralogical, will help.

The plutonic rocks must necessarily form the type families of any mineralogical classification of igneous rocks, and extrusive

[1] The actual percentages in the figures are ½, 1, 2, 5, 10, and 50.

[2] F. W. Clarke, "Data of Geochemistry," *U. S. Geol. Surv., Bull. 616*, (Washington, 1916), p. 432.

and hypabyssal rocks must be regarded as modifications of these. In this paper the writer has given names only to the plutonic representatives of the few families considered, it being understood, of course, that the granite family includes rhyolites; the syenite family, trachyte; the monzonite, latite; etc.

The basis of the classification here proposed is a double tetrahedron (Fig. 9), each trihedral angle of which represents certain mineral constituents. If there were a geometrical figure having ten or twelve corners, each equally distant from each of the others, it would have been possible to use a single mineral at a corner. Since there is no such figure, and rocks must be located with reference to all of the minerals which occur in them, it was found necessary to divide the minerals into as many groups as there are corners in a tetrahedron. But quartz and the feldspathoids never occur together, so it was possible to make the classification in five dimensions by using two tetrahedrons with a common base (Fig. 9). This arrangement was found to answer the purpose admirably, for the relationships between rocks which may contain either quartz or nephelite, etc., and which appear anomalous in the old classifications, are clearly shown.

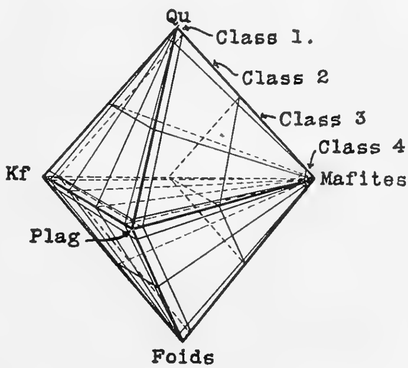


FIG. 9.—Subdivisions of the double tetrahedron into classes.

The groups of minerals represented by the corners of the double tetrahedron are: (1) quartz (symbol Qu[1]); (2) potash feldspars (symbol Kf), including the orthoclase molecule in anorthoclase;

[1] In the figures in this paper the quartz corner is indicated by the symbol Qu. The letter "f" is used for feldspar, therefore Kf indicates the potash-feldspars—orthoclase, microcline, and the orthoclase molecule in anorthoclase; Naf indicates albite and the soda molecule in anorthoclase, while Ca*Na*f represents the acid plagioclases and Na*Ca*f the basic plagioclases, the element in excess being given in italics temporarily to avoid confusion, although there need be none if one thinks of the symbol as reading calcium-bearing soda feldspar for the acid plagioclase and soda-bearing calcium plagioclase for the basic. Caf is used for anorthite, and Foids for the feldspathoids, lenads being unavailable from its use for certain normative minerals of the C.I.P.W. system.

(3) all plagioclases and the albite molecule in anorthoclase; (4) all feldspathoids; (5) the mafites,[1] including the ferromagnesian constituents, the "ores," etc., as given below.

As shown in Fig. 9, the double tetrahedron is unsymmetrically divided on certain faces by the traces of planes parallel to the quarfeloid[2] faces; on others, by lines parallel to one side as well as by lines converging to one of the angles. Experiments were made with symmetrical divisions of various kinds, but it was found impossible to fit the rocks as now named into compartments so made. It is true that new names might have been devised for such subdivisions, but it was not thought desirable to discard entirely the old and well-tried classifications which have very much to recommend them besides the fact that they have been so long in use. The old classifications are unsymmetrical, for we speak of a rock as a quartz-syenite, quartz-monzonite, quartz-diorite, etc., when it contains any amount of quartz. With respect to this mineral, therefore, the classification is based upon its ratio to the sum of all the other constituents, and the lines of division must be parallel to a side of the tetrahedron. The same is true also of the feldspathoids. In the divisions according to the feldspars, however, we find, for example, that a rock is a quartz-monzonite whether the percentage of feldspar among the light constituents is 10 or 90. Here the divisions are based upon the ratio of the feldspars to each other, irrespective of what their amount may be in the rock. The division lines, therefore, must converge toward the quartz and feldspathoid corners, as shown in Fig. 9.

[1] When the writer proposed (*Jour. Geol.*, XIX [1911], 319) the term "femag" as a substitute for ferromagnesian minerals which are not minerals of the norm, he did not stop to consider its euphony or whether it fitted into the C.I.P.W. terminology, but thought of it only as a term to take the place of "femic," which was being misused. He is perfectly willing to substitute "mafic" as an adjective, as proposed by the authors of the C.I.P.W. system (*Jour. Geol.*, XX [1912], 561). He wishes to use here a term for all the dark minerals of a rock except those that are pneumatolytic, and therefore uses "mafite" as a noun, feeling at liberty to include in it, since the word has not been used before, certain iron minerals, as listed below.

[2] C.I.P.W. suggest "felsic" as an adjective for the minerals quartz, feldspars, and feldspathoids. The writer here uses "quarfeloids" (QUARtz, FELdspar, feldspathOIDS) as a noun for these minerals in the front faces of the double tetrahedron, "felsite" being unavailable from its use as a rock name. "Leucocrates" cannot be used, since all light-colored minerals are not included.

The igneous rocks may be divided into various *classes* according to the percentage of dark constituents present. Any number of divisions might, of course, be made; Shand[1] proposed twelve, though more for descriptive purposes than classificatory. It is, however, not desirable in a classification to multiply excessively the number of classes into which the rocks are divided, and they may be gathered into rather large groups. Tentatively four classes have been made: (1) rocks with less than 5 per cent of dark constituents, (2) dark constituents between 5 and 50 per cent, (3) dark constituents between 50 and 95 per cent, and (4) dark constituents more than 95 per cent. Now since these division lines represent planes parallel to the two quarfeloid planes (quartz-feldspars and feldspars-feldspathoids), Fig. 9, they form similar triangles whose sizes represent the amounts of light constituents, decreasing with increase in dark constituents and approach to the mafite corner. For convenience, however, since they are similar they may be represented by triangles of the same size.

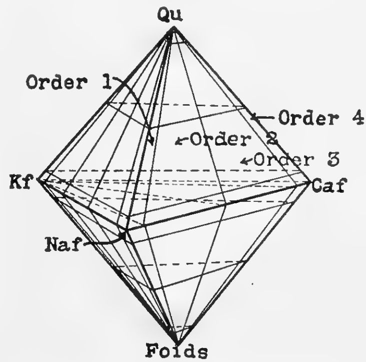


FIG. 10.—Subdivisions of the secondary double tetrahedron into orders.

Thus far the classification is one of five dimensions. But this is not enough. The kind of plagioclase in the rock must be taken into consideration. To bring this factor into the classification, imagine the lozenge-shaped quarfeloid plane to consist of two sheets of paper fastened together only along the Qu-Kf-Foids edge. If now the loose corners of the two sheets be separated a distance equal to a side of the original triangle, a new double tetrahedron will be developed, the horizontal line along which it was opened representing all plagioclases, the ends being formed by the Ab and the An molecules (Fig. 10). The same thing can be done, of course, with the double triangles representing the other classes, and the classification will now be made up of four double tetrahedrons,

[1] S. J. Shand, *op. cit.*, p. 404.

one for each class, the corners being formed by quartz, potash-feldspar, albite, anorthite, and the feldspathoids. But these tetrahedrons may be subdivided into *orders*. Based on the old classifications, these orders depend upon the proportions of the albite to the anorthite molecule; consequently the divisions must be made by planes all of which cut the quartz–potash-feldspar–feldspathoid edge but separate across the central plane of the double tetrahedron, as shown by the dotted lines in the figure, or by Fig. 11, which is a horizontal section through the center. That is, the edge Qu-Kf-Foids remains common to all of the divisions, the plagioclase corner simply having been changed. Now while the triangles formed by the intersections of these planes with the tetrahedron (Fig. 10) are not all equilateral, *the relative position of any rock plotted on an equilateral triangle on the basis of the three components represented by its corners and reduced to 100 will be the same as the same rock plotted with four components within the solid tetrahedron.* Consequently the different orders also may be represented simply by a series of double equilateral triangles (Figs. 20–23 or 24–26) whose right-hand corners vary with the kind of feldspar. It would, of course, be possible to make 20 or 100 or more different orders based upon variations of 5 or 1 or some other percentage in the albite content, but this is neither desirable nor necessary. Here the divisions have been made (1) albite ($Ab_{100}An_0$ to $Ab_{95}An_5$), (2) oligoclase and andesine, (3) labradorite and bytownite, (4) anorthite (Ab_5An_{95} to Ab_0An_{100}), giving four orders. In other words, the dividing points between albite and anorthite are 100–95–50–5–0 of the albite molecule.

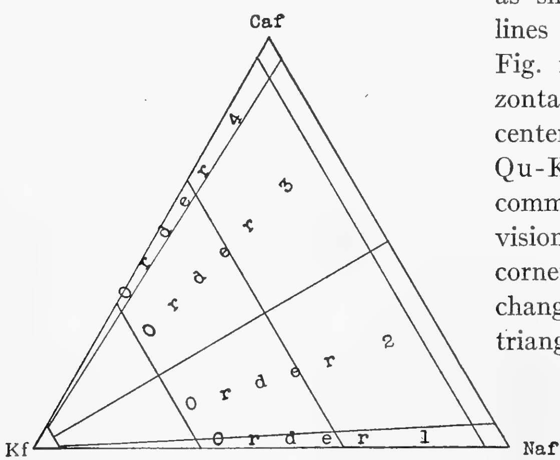


FIG. 11.—A section through the central plane of Fig. 10

There are now six dimensions in the classification, and since each pigeonhole will represent not only a plutonic rock but also a hypabyssal and an extrusive, we may say we have a classification in seven dimensions, yet every rock may be shown by a single point on a drawing in a single plane. The more detailed description which follows may make this clearer.

NUMBER AND POSITIONS OF THE VARIOUS DIVISION LINES

Classes.—The dividing lines between the various classes, orders, families, etc., were not selected at random, but an attempt was made to see if they have any logical positions. For this purpose the writer has been collecting data on cards for all rocks whose modes in mineral percentages have been determined. The number is small, less than 600 such rocks having been found. Unfortunately this number is too small to determine definitely all points, but the writer found that in most cases preliminary graphs with fewer analyses showed practically the same curves as the ones here given.[1]

In order to determine the positions of the dividing planes between the light and the dark rocks, and to decide whether there should be four or five classes (namely white, light, medium, dark, and black), the rocks of the various families were plotted in Fig. 12, in which the abscissae represent the proportions of light constituents in the rock and the ordinates the number of rocks whose modes were known, the percentages being gathered by fives to make a smoother and more representative curve than the individual percentages would have made. The lower curve in the figure is the curve of *all* rocks (585) of which the writer had the modes, and includes the alcalic rocks as well as the families given in the upper curves. All the curves except the one for gabbro, which does not extend so far, show an increase at 90–95 per cent light and a decrease beyond that toward 100 per cent. Consequently rocks may well be called leucocratic when there are 95 per cent or more of light minerals; and there is no objection to making the melanocratic division beyond 95 per cent dark. A difficulty appears in

[1] Since this paper was written, 91 additional mode-analyses have been found, but the graphs remain practically as they were.

making a third division. In the granite and syenite, monzonite and quartz-monzonite, syenodiorite and granodiorite families a line separating 50 per cent light from 50 per cent dark would throw practically all of the rocks on the same side. With respect to diorite and quartz-diorite the curve is not good, owing to insufficient data, and it shows no definite maximum. The gabbro-curve has its maximum at 60 per cent light. With the gabbros

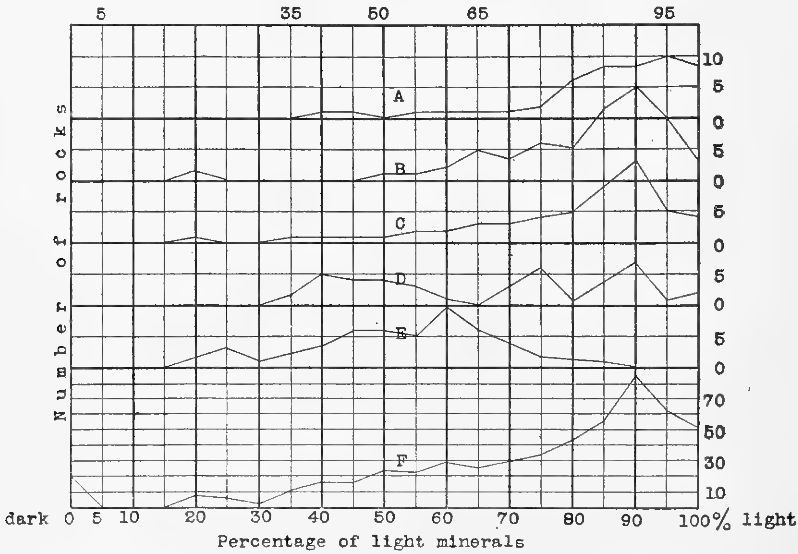


FIG. 12.—Curves showing the number of rocks with various percentages of light and dark constituents: *A*, granite and syenite; *B*, quartz-monzonite and monzonite; *C*, granodiorite and syenodiorite; *D*, quartz-diorite and diorite; *E*, quartz-gabbro and gabbro; *F*, all rocks.

and diorites it might be better to make five classes with dividing lines at 0–5–35–65–95–100 instead of at 0–5–50–95–100, yet the 65 per cent light line cuts the gabbro-curve at rather a high point. The addition of a fifth class for rocks with approximately equal amounts of light and dark constituents would increase the total number of families by 104, and to the writer it seems undesirable to do this. Not much is gained, and it is just as well to speak of light and dark gabbros, separating on the 50–50 line, as to make the main gabbro class the intermediate 35–65 position. In the lowest curve, which

represents all rocks, there are no sharp division lines except at 5 and 95 or thereabout. The central division points could equally well be 50–50 or 35 and 65. On the whole, the writer thinks the 50–50 line best, but leaves this question open for the present.

Lincoln[1] makes three divisions, leucocratic, mesocratic, and melanocratic, according to the percentages of light constituents, with division lines at 0–33–67–100; and in the expanded series, five divisions at 0–4–33–67–96–100.

Iddings[2] separates his rocks on the ratios 0–$\frac{3}{8}$–$\frac{5}{3}$–100; that is, into rocks with less than $37\frac{1}{2}$ per cent dark, between $37\frac{1}{2}$ and $62\frac{1}{2}$ per cent, and with more than $62\frac{1}{2}$ per cent. This makes the first and third groups very large. Even the C.I.P.W. general subdivisions of 0–$12\frac{1}{2}$–$37\frac{1}{2}$–$62\frac{1}{2}$–$87\frac{1}{2}$–100 would make the first and last groups too large, for rocks with $12\frac{1}{2}$ per cent of dark constituents (see Fig. 7 with 10 per cent) certainly are not leucocratic. Furthermore, a division at $12\frac{1}{2}$ or $37\frac{1}{2}$ per cent at the leucocratic end is not so logical as at 5 per cent (cf. Fig. 12). Shand[3] makes his divisions at 100–97–90–80–70–60–50–40–30–20–10–3–0 per cent light minerals. These, however, are too many for the purpose of classification, the essential difference between rocks with 60 and 70 per cent of dark constituents, for example, being insignificant. From the curves in Fig. 12 there appears to be little choice between dividing lines at 33, 35, $37\frac{1}{2}$, or 50. If there is any, it is in favor of 50–50.

Orders.—Having divided the rocks into four (or five) classes according to the amount of dark constituent, they may be divided into orders on the basis of the plagioclase.

In determining the kind of plagioclase in a rock, it has been quite customary to give the Ab-An percentage in simple round numbers, such as Ab_2An_3, Ab_1An_1, etc. This produces an excessive number of rocks at these points, as is clearly brought out in Fig. 13, which is less valuable for that reason. As may be seen, there are crests at Ab, Ab_3An_1, Ab_2An_1, Ab_1An_1, Ab_3An_5, and Ab_0An_{100}. Having no other marked crests in the curve indicating natural division lines, the writer has taken the points 0–5–50–95–100,

[1] F. C. Lincoln, *op. cit.*, 556.

[2] J. P. Iddings, *op. cit.*, II, 150, 308.

[3] S. J. Shand, *op. cit.*

thus grouping albite (allowing up to $Ab_{95}An_5$ for latitude), oligoclase and andesine, labradorite and bytownite, and anorthite (with Ab_5An_{95} for latitude), and conforming to the present lines of separation between the alkali rocks, the acid plagioclase (dioritic) rocks, the basic plagioclase (gabbroic) rocks, and the anorthite rocks.

Each of the first three classes of rocks may be divided in this manner into four orders, making twelve orders in all. The fourth class, that is, the one in which the dark constituents form over 95 per cent of the rock and the light constituents, including the feldspars, only 5 per cent, naturally cannot be divided on the basis of the feldspars; consequently its orders are differently formed.

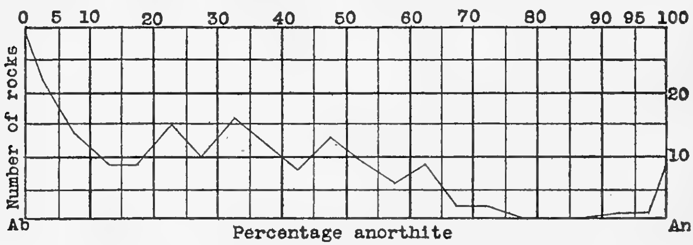


FIG. 13.—Number of rocks with various plagioclases, all families from 0 to 31 included.

Lincoln does not divide his rocks on the kind of plagioclase, but separates his gabbro from diorite, for example, simply on the basis of its leucocratic or mesocratic character, which is not according to common usage.

Iddings[1] unites his orthoclase with albite and uses the ratio of orthoclase plus albite to other plagioclases, and makes his divisions[2] at the points $0-\frac{7}{1}-\frac{5}{3}-\frac{3}{5}-\frac{1}{7}-100$; that is, at $0-12\frac{1}{2}-37\frac{1}{2}-62\frac{1}{2}-87\frac{1}{2}-100$ per cent. These divisions are not quite comparable to the present writer's triangular divisions into the Kf, Naf, and Caf ratios. Owing to the fact that soda is of more importance in connection with the lime of the plagioclases than it is in connection with the potash of cryptoperthite, it seems more reasonable to separate Kf from Naf+Caf than to separate Kf+Ab from the plagioclase minus albite. The latter would be simpler in placing microperthite, but

[1] J. P. Iddings, *op. cit.*, II, 41. [2] *Ibid.*, pp. 38, 40–41, 42, 44.

is incorrect in theory. Tyrrell[1] says that Iddings' system is faulty in this respect, and suggests uniting all the soda molecules with orthoclase, and comparing the sum with the lime molecules. But to this the objection may be made that it fails to separate the soda- from the potash-rocks. Personally the writer prefers to go one step farther and separate the three molecules, as shown in Fig. 11. If Kf and all the Naf were united, it would make difficulty in the monzonite group where the Ab molecule must be separated from the An. Thus with the potash and soda united, a rock with 50 per cent orthoclase and 50 per cent andesine ($Ab_{60}An_{40}$) would give $(Or+Ab)_{80}An_{20}$, while if classified by the ratio of orthoclase to albite plus anorthite it would give Or_{50} $Plag_{50}$. The difficulty in determining the albite in most microperthite is not great; the amount can be estimated with little error.[2] Of course this is not possible in anorthoclase, and rocks containing much of this mineral will have to be determined chemically. Ordinarily, however, the amount of soda is too small to change the classification of the rock, even if neglected. In rocks which contain known amounts of soda-orthoclase and plagioclase, the molecules must be separated. Thus a ciminite from the Roman Comagmatic Region[3] contains soda-orthoclase (Or_6Ab_1) 43.6 per cent and labradorite (Ab_1An_2) 16.1 per cent, which gives orthoclase 37.4 per cent and albite 6.2 per cent from the soda-orthoclase, and albite 5.4 per cent and anorthite 10.7 per cent from the labradorite. Uniting these there is orthoclase 37.4 per cent, albite 11.6 per cent, and anorthite 10.7 per cent. This gives $Ab_{52}An_{48}$, the point falling just on the Ab side of Ab_1An_1 or in Order 2, and $Kf_{63}Plag_{37}$, which brings the rock in the row of families 3, 8, 13, etc. (Fig. 16). Zonal feldspar may be determined by considering the approximate amounts of each kind and obtaining the average Ab-An value. This will be necessary in but few cases, for ordinarily it may be determined by inspection whether the

[1] G. W. Tyrrell, "A Review of Igneous Rock Classification," *Science Progress*, No. 33 (July, 1914), 79.

[2] For figures giving a comparison of measured and calculated values see Eero Mäkinen, *Bull. com. géol. Finlande*, No. 35 (1913), p. 74; Charles H. Warren, *Proc. Amer. Acad. Arts and Sciences*, LI (1915), 127–54.

[3] H. S. Washington, *op. cit.*, p. 65.

average runs across the $Ab_{50}An_{50}$ line. Of course if the nucleus as well as the rim falls entirely between the 0–5, 5–50, 50–95, or 95–100 lines, there is no need for computation unless it be to determine the exact position of the rock in the triangle.

Families.—The quarfeloid face of the double tetrahedron (Fig. 9), or any face parallel to it, will appear as shown in Fig. 16. To locate the lines separating the various families it was necessary to determine the logical divisions in two directions; namely, between

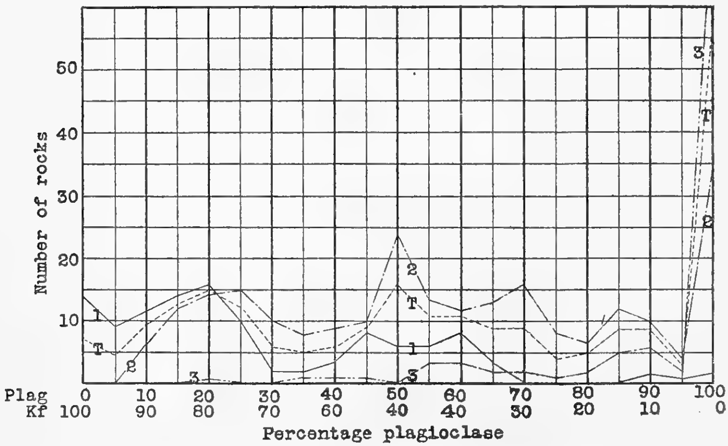


FIG. 14.—Ratios of Kf to plagioclase in Families 1 to 15, Orders 1 to 3, and totals. Vertical scale of totals is one-half of other curves. The numbers indicate the orders.

the potash feldspar and the plagioclase and between rocks with or without quartz or feldspathoids.

In Fig. 14 the curves for the proportions of potash-feldspar to plagioclase are shown for Orders 1, 2, and 3 and for the sum of all feldspathoid-free rocks; the writer having no mode-analyses showing potash-feldspar with anorthite in Order 4. The curves show rather excessive increases on the 50–50 line, due to the fact that many writers speak of labradorite as Ab_1An_1; the deduction of rocks where this was done would slightly reduce the lines. In all the curves the dividing lines may be made at 0–5–35–65–95–100, corresponding to the subdivisions in vogue of alkali-granite, granite, quartz-monzonite, granodiorite, quartz-diorite, etc.

The vertical direction of Fig. 16 gives the quartz percentage. In Fig. 15 are plotted the curves for the proportion of quartz among the light constituents for all rocks in the upper triangle (Families 0 to 15, Fig. 16), and separate curves for Orders 1, 2, and 3. The separation at 5 is clear. There may be a question whether the upper division of quartz should be made at 95, 90, or even at 65. For symmetry, of course, it should be at 95. With respect to a line at 50, the writer is in doubt. Practically all the rocks fall below 50 per cent quartz (that is, quartz is less than 50 per cent of the

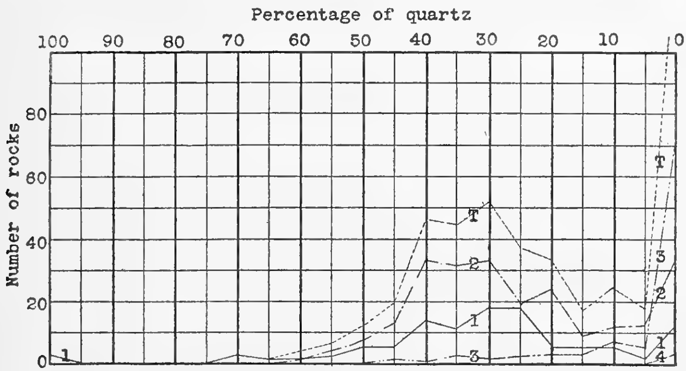


Fig. 15.—Percentage of quartz among the light constituents, recalculated to 100. Curves for Orders 1, 2, 3, 4, and totals. The numbers indicate the orders.

light constituents, consequently it forms even less than 50 per cent of all the constituents of the rock). It would be possible to group all the rocks given in Families 2 and 7, 3 and 8, 4 and 9, etc. (Fig. 16), together, and call those falling in the upper divisions simply quartz-rich granites, etc. However, since there are so few rocks here, it may make it all the more desirable to divide on the 50–50 line. This would make uniform divisions everywhere in the system at 0–5–50–95–100 except for the Kf-Plag ratio. Of course the retention of the line at 50 in this and the lower triangle makes 8 or 10 more families in each order of the first three classes, or a total of 102. However, if these families are simply numbered and the rocks called quartz-rich granite, quartz-rich granodiorite, nephelite-rich nephelite-syenite, etc., it will add no new names and make clearer the positions of the rocks. Curves drawn for the

feldspathoid rocks are similar to those in Fig. 15, but are somewhat more irregular owing to insufficient data.

The families are to be numbered as shown in Fig. 16. The object in beginning with 0 is to make the positions easier to remember, since they run in groups of five. Furthermore, Family 0 occurs only in Order 1, as do also Families 1, 6, 11, 16, 21, 26, and 31, for they form the hinge about which the order tetrahedron (Fig. 10) was opened, and are the same in all. This is shown in Figs. 21 to 23, where these families are omitted and represented by dotted lines. Instead of having 12×32 families, therefore, there are 3×32 families (in the first orders in each of the first three classes) $+ 9 \times 24$ families (in Orders 2, 3, and 4) $+3 \times 15+1$ families (in Class 4, to be mentioned later), making 358 families in all. If Order 1 is omitted, as suggested in question 4, below, the total families will be 286, and if Order 4 is united with Order 3 there will be only 214. Although the maximum number of families is 358, it does not mean that there are 358 names to learn, for the light and dark rocks may be separated by prefixes without making awkward names; thus leuco-granite, melano-granite, etc.

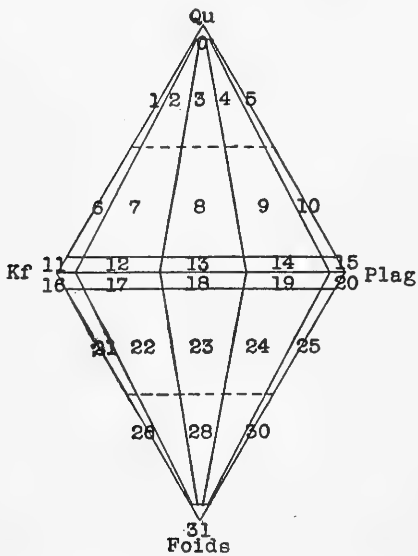


FIG. 16.—Family numbers in Classes 1 to 3.

The divisions made by other writers may now be compared with Figs. 14 and 15. Lincoln uses the ratio orthoclase to all plagioclase, the latter not differentiated as is done here. His percentages are 100–96–67–33–4–0.

It is rather difficult to compare the divisions proposed by Iddings with those proposed by Lincoln or by the present writer, for, as mentioned above, he unites albite with the potash feldspar and

compares this sum with the remaining plagioclase; that is, he has the ratio

$$\frac{\text{Kf+Ab in albite}}{\text{Ab in soda-lime feldspar+all An}}\,.$$

His divisions are,[1] as mentioned under "Orders," above, 100–$87\frac{1}{2}$–$62\frac{1}{2}$–$37\frac{1}{2}$–$12\frac{1}{2}$–0.

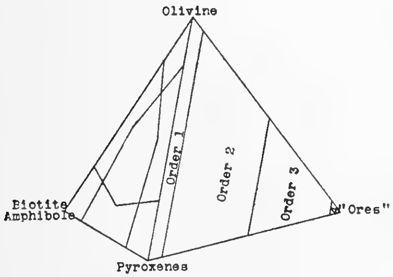


FIG. 17

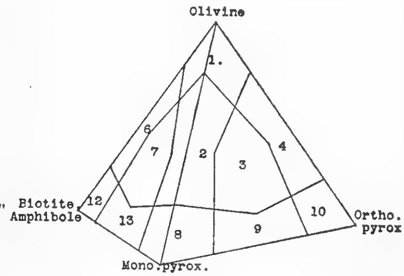


FIG. 18

FIG. 17.—Subdivisions of the tetrahedron of Class 4 into orders

FIG. 18.—Subdivisions of Orders 1 and 2, Class 4, into 15 families. Order 3 is subdivided similarly, but the corners represent olivine, biotite and amphiboles, pyroxenes, and the "ores." Order 4 has the various "ores" for corners.

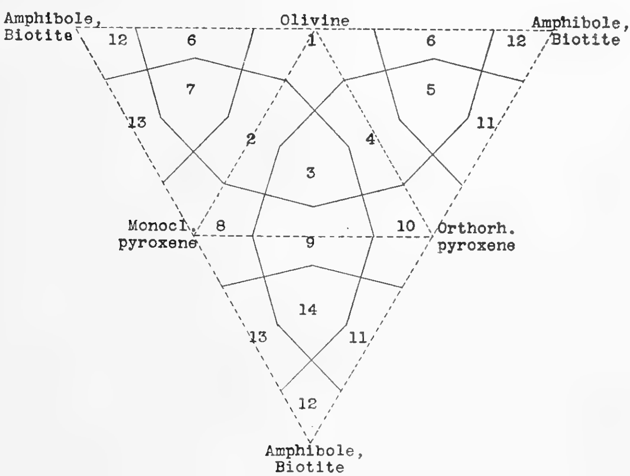


FIG. 19.—Family numbers in Class 4

The quartz- (or feldspathoid-) feldspar relations given by Lincoln are 100–96–67–33–4–0, and by Iddings[2] 100–$62\frac{1}{2}$–$12\frac{1}{2}$–0. Lincoln's division at 33 does not fit at all well into Fig. 15. Idding's divisions

[1] J. P. Iddings, *op. cit.*, II, 38, 40–41, 42, 44. [2] *Ibid.*, pp. 32, 38, 147, 228, 292.

fit quite as well as the divisions 100–95–50–5–0 proposed in the present paper, but the writer feels that a rock with $12\frac{1}{2}$ per cent quartz (see Fig. 7 with 10 per cent) is too rich in quartz to be called a syenite. The writer would have no objection to making the divisions at 100–95–65–5–0 quartz (or feldspathoids), that is, on the basis of the 100–95–56–35–5–0 divisions with the omission of the 35 per cent line, but thinks it better to leave the divisions symmetrical. A rock with over 50 per cent quartz or feldspathoid is certainly distinct enough to deserve a separate place.

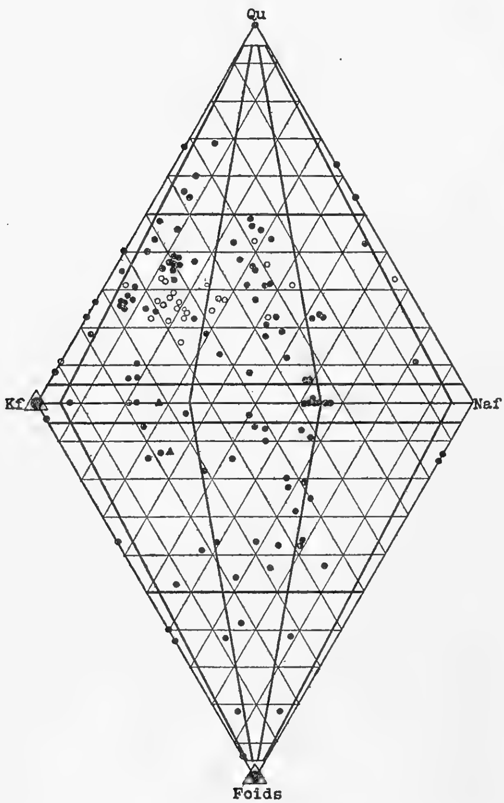


FIG. 20.—Rocks of Order 1 falling in Classes 1 to 3. Open circles are rocks of Class 1, dark circles rocks of Class 2, and triangles rocks of Class 3.

Class 4.—Owing to the absence of light constituents in Class 4 it was necessary to make the subdivisions on a different basis. After numerous attempts with different figures and different groupings of minerals, it was found that the compartments shown in Fig. 17 correspond most closely to the present subdivisions of the melanocratic rocks. The tetrahedron is subdivided into four orders by planes parallel to the left-hand face, each order representing an increasing amount of the ores. The division points for these planes, as in the other classes, are 0–5–50–95–100. To accommodate the rocks of the old classification, each order triangle

was opened out at one corner into a secondary tetrahedron, as shown in Fig. 18. The division points between families are at 0–25–75–100 to make the nomenclature conform to the older systems, and they are numbered, from the top and counterclockwise, from 1 to 15. The four corners, in Orders 1 and 2, represent respectively olivine, biotite and amphibole, monoclinic pyroxene, and orthorhombic pyroxene. In Order 3 the corners are olivine, biotite and amphibole, the pyroxenes, and the "ores" and other dark constituents. In Order 4, if thought desirable, they may be taken to represent the various ores; the writer, however, groups the ores in one family, for, considered as rocks, they are unimportant and hardly worth while separating. All of the families of the whole class, except Family 15, appear on the surface of the tetrahedron, Families 5 and 11 being at the back of Fig. 18, Family 14 underneath, and Family 15 in the center. Fig. 19 shows the tetrahedron opened out, Family 15 alone not appearing.

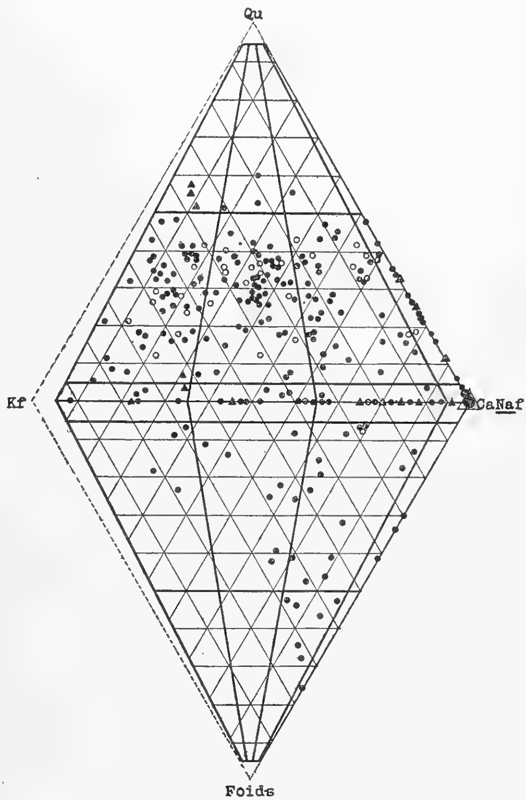


FIG. 21.—Rocks of Order 2 falling in Classes 1 to 3

ROCKS INCLUDED IN THE VARIOUS FAMILIES

Computed by the rules which follow, nearly 600 rocks are represented in Figs. 20 to 23. In these diagrams the rocks of the

same order, though of different classes, are shown together, the leucocratic rocks of Class 1 being represented by open circles, the moderately dark rocks of Class 2 by dark circles, and the dark rocks of Class 3 by triangles. The larger circles and triangles indicate that a number of mode-analyses fall together at these points. It will be seen that there are 32 families represented in Fig. 20, while in the other three figures there are only 24 to the order, as explained above.

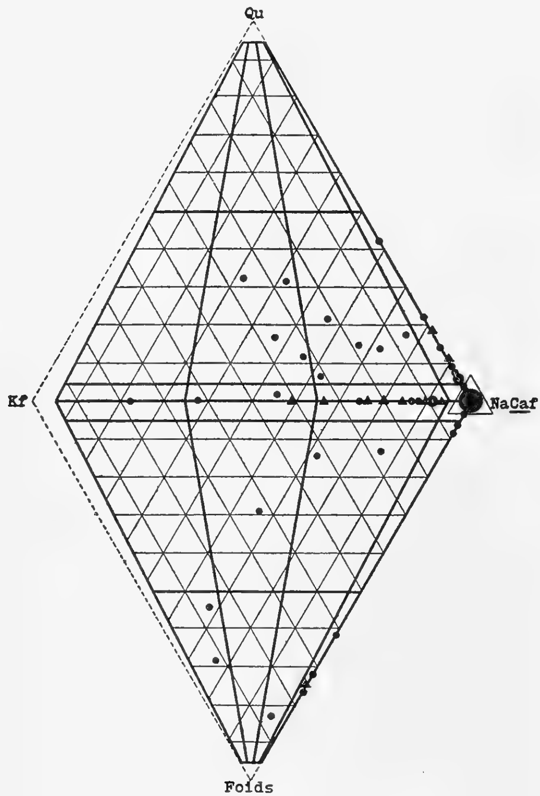


FIG. 22.—Rocks of Order 3 falling in Classes 1 to 3

In the following list about 500 computed rocks are arranged according to their old names followed by numbers indicating their positions in the present classification. No rocks are given having less than three mode-analyses unless of well-defined recent rocks. The first figure in the following numbers represents the class, the second the order, and the third (or third and fourth) the family. There are no orders in Families, 0, 1, 6, 11, 16, 21, 26, and 31, but since the rocks of these families are plotted in the double triangles of Order 1, their positions may be indicated by the figure 1. The figures in parentheses indicate the number of determined rocks which fell into that family. For example, 2123, 118, 422, 4210 represent respectively Class 2, Order 1, Family 23;

Class 1, Order 1, Family 8; Class 4, Order 2, Family 2; and Class 4, Order 2, Family 10. Numbers in bold-face type in the list indicate proper families among scattered (misnamed) rocks.

The rocks may seem rather scattered, but upon careful comparison it will be seen that they are not so far apart as they appear at first sight, for the lighter and darker rocks of Classes 2 and 3 in the gabbro and diorite families and of Classes 1 and 2 in the granite, syenite, monzonite, etc., families have ordinarily not been separated in petrographic reports. Much of the variation, of course, is due to the loose naming of rocks, and an andesine-bearing rock with augite may have been named gabbro, and a mesocratic labradorite-augite rock, diorite, etc. Thus the basalts in the list below—2315(4), 3215(1), 3315(5)—include 9 rocks belonging to Order 3, Family 15, the normal gabbro-basalt family, 4 of the rocks being mesocratic and 5 melanocratic. The remaining rock (3215) is a melanocratic andesine-bearing rock which should have been called an andesite.

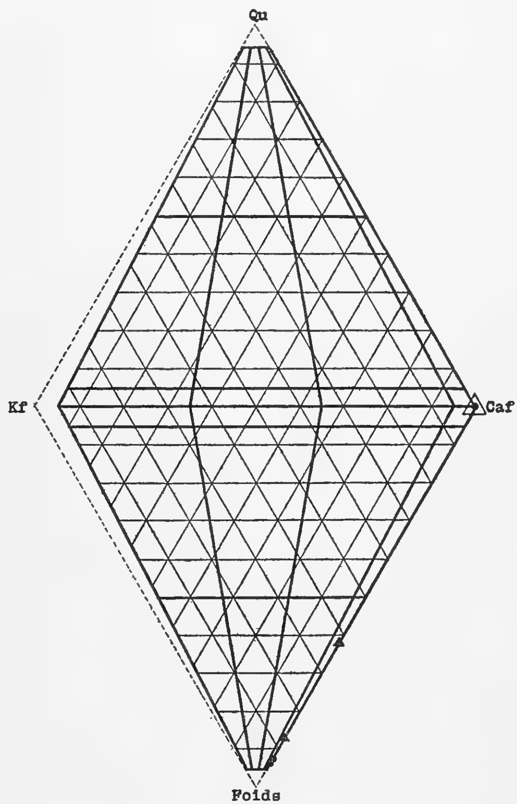


FIG. 23.—Rocks of Order 4 falling in Classes 1 to 3

Andesite **2215**(6), **3215**(1).
Aplite 128(3), 217(1), 223(1).
Alaskite 118(2), **117**(2), 128(1).

Basalt **2315**(4), 3215(1), **3315**(5).
Basalt, Quartz **2310**(3).
Bostonite 2114(1), 2112(1), 2214(1).
Camptonite **3215**(2), 3214(1).
Comendite 217(1).
Covite 2123(1).
Diabase 2215(1), **2315**(9), 3215(1), **3315**(4).
Diorite 2214(2), **2215**(4), **3215**(2).
Diorite, Quartz **2210**(6), 238(1), 239(4), 2310(3).
Essexite 2320(1), 2315(1), 2324(2), 3213(1), 3314(2).
Gabbro 2314(1), **2315**(14), 3314(2), **3315**(5).
Gabbro, Quartz **3310**(3).
Gauteite 2320(1), 2330(1).
Granite, including alkali-granite **117**(4), 118(1), 123 (1), **127**(3), 128(2), 211(1), 212(4), **217**(20), 218(8), 219(1), **227**(21), 228(27), 229 (16), 2210(6), 238(1), 2310(1).
Granite-porphyry 212(1), 216(1), 227(2).
Granodiorite 228(2), **229**(8).
Grorudite 218(6), 219(2).
Hedrumite 2123(1), 2114(1), 2124(1).
Hornblendite **4212**(1), **4112**(1).
Heumite 2223(2), 2224(2).
Ijolite 2131(5).
Kersantite 2214(1), **3215**(2), **3315**(1).
Leucitite 2131(1), 2229(1), 2230(1), 2329(1), 2430(2), 3430(1).
Lindoite 228(5).
Laurdalite 2124(1), 2224(1).
Laurvikite 2118(1), 2123(1).
Leucite-tephrite 2223(5), 2224(4), 2229(3), 2327(1), 2230(2).
Malchite 3210 (3).
Melilite-basalt 2315(3).
Minette 216(2), 2111(1), 227(1), 2212(1), **2215**(1).
Minette, Soda 2114(1), 229(1), 2214(2).
Mariupolite 2125(2).
Missourite 3131(3).
Monmouthite 2131(1).
Monzonite **2213**(5), **2313**(1), **3213**(1), 3214(1).
Monzonite, Quartz **128**(4), 129(1), **228**(7), 229(4), 2214(1), **238**(3), 322(3).
Nephelite-syenite 1224(1), **2122**(3), 2123(3), 2124(1), 2126(1), 2129 (1), **2222**(3), 2223(1), 2225(1).
Norite 2214(1), 2314(3), 3214(1), 3314(5), **3315**(5).
Pantellerite 218(3).
Pegmatite 117(7), 118(2), 127(1), 129(4), 1210(2).
Phonolite **2122**(2).

Rockallite 215(2).
Rougemontite 2415(1).
Rouvillite 2225(1).
Shonkinite 2112(1), **3112**(1), **3212**(1).
Solvsbergite 2112(2), 2113(4), 2123(2).
Syenite 2111(2), 2113(3), 227(11), 228(7), 229(1), **2212**(2), 2312(1), 2313(1), **3212**(1), 327(1).
Tawite 2127(1).
Tinguaite **2122**(1), 2123(4), 2124(3), 2116(1).
Trachyte 216(1), 2113(1), 2123(1), **2212**(1), 2213(2).
Vulsinite 2213(1), 2222(1), 2223(2).
Yamaskite 3415(3).

CLASS NAMES

In a few cases the old classifications give special names to the dark varieties of feldspathic rocks. Thus shonkinite was definitely defined as a syenite with more than half of the constituents dark, although in the foregoing list one rock (2112) is mesocratic. In most cases, however, there are no special names for the dark feldspathic rocks, nor is it necessary to invent such, for the different varieties may be distinguished by prefixes. Since the rocks of Class 4 are separated from each other on an entirely different basis from the rocks of the other three classes and have special names they need not be considered here. To the other three classes the names suggested by Brögger—leucocratic, mesocratic, and melanocratic—may be prefixed. If desired, a rock may be called a leucogranite, meso-granite, or melano-granite, for example, instead of a leucocratic granite, mesocratic granite, etc. Meso, unfortunately, has been used as a prefix for Mesozoic rocks, but since the age classification of igneous rocks is no longer in use this would cause no confusion. Furthermore, since the normal rock usually falls in Class 2, the meso prefix is seldom necessary, and its name may be used without a prefix.

ORDER NAMES

The different orders may be indicated, when no special names exist for the various rocks, by the prefixes albite- (or soda-), sodic-, calcic-, and anorthite- (or lime-). Thus in the diorite family the rocks of the different orders would be albite- (or soda-) diorite,

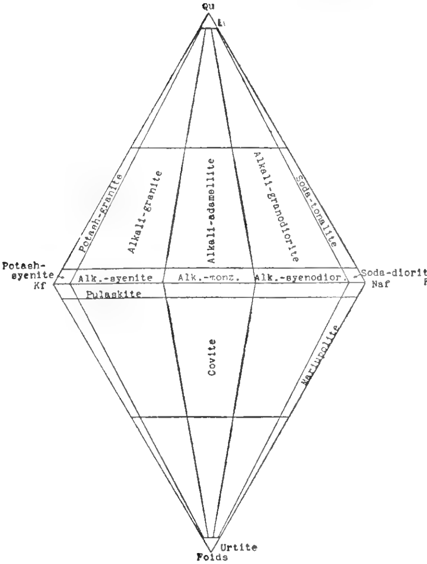


FIG. 24

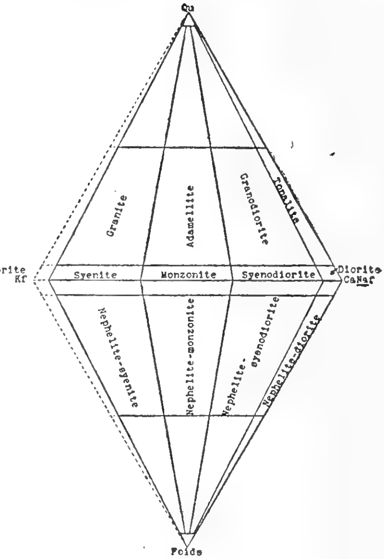


FIG. 25

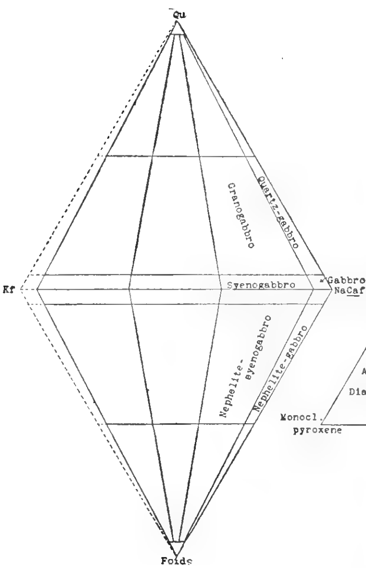


FIG. 26

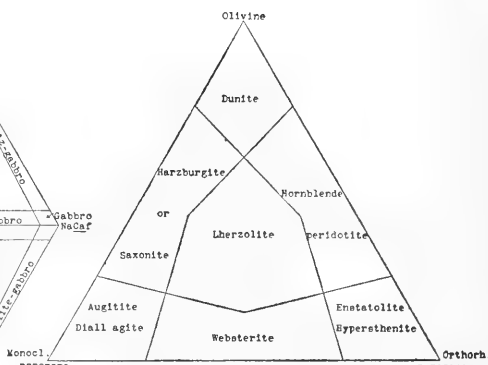


FIG. 27

FIG. 24.—Family names, Class 2, Order 1

FIG. 25.—Family names, Class 2, Order 2

FIG. 26.—Family names, Class 2, Order 3

FIG. 27.—Family names, Class 4, Order 1, Families 1, 2, 3, 4, 8, 9, and 10

sodic-diorite, calcic-diorite, and anorthite- (or lime-) diorite. As a matter of fact, these rocks in the old classification have special names, namely, soda-syenite, diorite, gabbro, and anorthite-gabbro, and, except the first, which more properly is an albite- (or soda-) diorite, should not be changed. The prefixes persodic, dosodic, etc., of the C.I.P.W. system cannot be used, since they apply to definite proportions of the constituents and not to those used here.

FAMILY NAMES

It is not the intention in this paper to name definitely all the families, those in Figs. 24 to 27 being given simply as examples. Most of the family names have been determined, and will be given in a succeeding paper. The family name should be that of a rock without abnormal constituents which occupies nearly the center-point of that family. Thus a garnet-bearing rock should not be chosen as a family representative if a non-garnetiferous rock is known, the garnetiferous rock being indicated by a prefix. The name should also be that of the plutonic rock, if such is known. Furthermore, if only one name is given to the rocks of the same family in the various classes, it should be given to Class 2; Class 1 will then be its leucocratic variety and Class 3 its melanocratic variety. It is not to be understood from this that the writer thinks it undesirable to name particular varieties, for it may be very desirable if they represent distinct types and if their relationships to known rocks are clearly shown; but if a new type differs only by the presence of a single abnormal constituent, that constituent should simply be used as a modifying name.

The reasons for using certain family names, such as adamellite for quartz-monzonite, tonalite for quartz-diorite, etc., will be given in a succeeding paper. Syenodiorite, syenogabbro, and granogabbro are introduced as new terms to fill definite positions, the last being the orthoclase-bearing variety of quartz-gabbro and analogous to granodiorite, the first two being the quartz-free varieties of granodiorite and granogabbro.

Sub-families in Orders 1, 2, and 3 are formed on the basis of the predominating dark or auxiliary constituent; thus under granite are the divisions biotite-granite, hornblende-granite, topaz-granite,

tourmaline-granite, etc. This applies whether the modifying constituent is a mafite or an auxiliary.

THE MINERAL GROUPS

It is not sufficient to divide the constituents of the rock into those that are light and those that are dark, but it is necessary to make certain definite groupings. The primary division, of course, is into quarfeloids and mafites. Under the former are included:

QUARFELOIDS

Quartz (Qu).
Potash feldspar (Kf), including orthoclase and microcline, and the orthoclase molecule in microperthite, anorthoclase, etc.
Plagioclase (Plag), including the albite molecule in anorthoclase as well as all plagioclases.
Feldspathoids (Foids), nephelite, leucite, sodalite, hauynite, noselite, melilite, primary analcite, primary cancrinite, eudialyte, etc.

The rear angle of the double tetrahedron represents the mafites. It is the position of the remainder after the quarfeloids and auxiliary constituents have been deducted.

MAFITES

Dark micas (biotite, phlogopite, etc.).
Amphiboles.
Pyroxenes (including uralitized pyroxenes).
Olivine.
Iron ores (magnetite, ilmenite, chromite, pyrite, hematite, etc.).
Cassiterite.
Garnet.
Primary epidote.
Allanite, zircon, rutile, and other dark minor accessories.

SECONDARY CONSTITUENTS

Secondary constituents are calculated as the originals from which they came. Thus ore replacements of the mafites are computed as mafites, kaolin as feldspar, chlorite as a biopyribole, cancrinite and analcite as feldspathoids, serpentine as a mafite, etc.

AUXILIARY CONSTITUENTS

Auxiliary constituents are constituents, mostly pneumatolytic or metamorphic, which may be used in the nomenclature as mineral modifiers in the formation of sub-families. Rocks containing these minerals may have independent names if desired. The auxiliary minerals are seldom of importance.

Topaz	Primary scapolite
Tourmaline	Muscovite
Cordierite	Lepidolite
Corundum	Zinnwaldite
Fluorite	Apatite, etc.
Andalusite	

It will be observed that most of the auxiliary constituents are light in color; they are, consequently, computed among the leucocrates. It is true that if this is done, tourmaline-granite will fall among the leucocratic rocks, but since this rock is aplitic and the mineral pneumatolytic, this is not undesirable.

Glass must be computed from an analysis. One can usually surmise its composition from the character of the phenocrysts and the appearance of the rock. When undetermined, the rock must be given a tentative name, such as hyaline-rhyolite, etc.

RULES FOR COMPUTING ROCKS FROM THEIR MODES

1. The sum of the minerals in the mode should be 100 ± 0.5. If less, recalculate[1] to 100. The sum of the leucocrates (quarfeloids plus auxiliary minerals) so obtained determines the class.

Class 1. Leucocrates form less than 95 per cent of the total rock.
Class 2. Leucocrates between 95 and 50 per cent.[2]
Class 3. Leucocrates between 50 and 5 per cent.
Class 4. Leucocrates less than 5 per cent.

2. Determine the orders in Classes 1, 2, and 3 directly from the Ab-An ratio, the division lines being 0–5–50–95–100. In rocks

[1] All of the necessary computations may be performed in an instant of time by means of a slide-rule.

[2] These classes are tentative. If thought desirable (see question 1, below), the rocks will be divided into five classes.

containing both anorthoclase and soda-lime feldspars, the three molecules Kf, Naf, and Caf are to be separated, and the orders determined by the total Ab-An ratio. (See above, under the heading "Orders," for an example of ciminite so separated.) In Class 4 the orders are determined by the percentage of "ores" and other dark minerals in the rock, the division points also being 0–5–50–95–100.

3. Determine the family. In Classes 1, 2, and 3 first recalculate the quarfeloids to 100. The amount of quartz (or feldspathoid) immediately determines the distance from the feldspar line. The separation points are 0–5–50–95–100. Now recalculate[1] the Kf plus plagioclase to 100, and determine the proper point on the Kf-Plag line. (If plotted graphically, the family is directly determined by the position of the intersection of the three lines. If the point falls very close to a division line, it may be necessary to compute its position accurately.) The separation points for Kf-Plag are 0–5–35–65–95–100.

In Class 4, Orders 1 and 2, recalculate the olivine, pyroxenes, biotite, and amphiboles to 100 and find the proper positions graphically, or find the position analytically by taking the ratio of the minerals of one corner to each of the others; thus augite to olivine, augite to hypersthene, and augite to biotite or amphibole. The division points are 0–25–75–100. In Class 4, Order 3, the corners represent olivine, amphibole and biotite, all pyroxenes, and the "ores" and other dark constituents. In Class 4, Order 4, the writer groups all the ores in a single family, but classifies the various hematite, ilmenite, magnetite, etc., ores as subfamilies. If desired they may be further separated. If accessory dark minerals, not used in the computation, are abundant, they determine subfamilies and may be mentioned in the rock name.

A few points to be observed.—Any percentage value falling exactly on a line should be moved in the direction of the center of the triangle. Thus a syenite with 5 per cent quartz is classified with granite, a rock with 95 per cent mafites belongs to Class 3,

[1] It is immaterial whether the orthoclase-plagioclase ratio is taken from the original values or from those reduced as quarfeloids to 100. The results are naturally the same.

and one with 95 per cent quarfeloids to Class 2; $Ab_{95}An_5$ belongs to Order 2 and Ab_5An_{95} to Order 3. If the divisions fall on the 50–50 line of quartz they are moved upward, or, with the Foids downward, toward the apex; that is, they are placed in Families 1 to 5 or 25 to 30. Along the plagioclase line, $Ab_{50}An_{50}$ is classed with the basic plagioclase, and 50–50 light-dark with the dark. Rocks falling on the line separating the two triangles, namely, on the feldspar line, should be classed on the quartz side, that is, on the normal side.

EXAMPLES

Example 1.—A granodiorite having the composition

Quartz	18.0		=23.1
Orthoclase	18.0		=23.1
Andesine (An_{70} An_{30})	42.0		=53.8
Total quarfeloids		78.0	
Biotite	12.8		
Hornblende	9.0		
Magnetite	.1		
Titanite	.1		
Total mafites		22.0	
		100.0	

Percentage quarfeloids = 78. Rock belongs to Class 2.

$Ab_{70}An_{30}$ falls between 95 and 50. The order, therefore, is 2.

The family may be rapidly determined graphically, Plot 23.1 Qu, 23.1 Or, and 53.8 Ca*Na*f by measuring 23.1 upward from the base of the triangle toward Qu, and 23.1 from the right-hand inclined line toward the lower left corner. The intersection of the two lines will fall in Family 9 and determines the position of the rock. As a check, the point must also lie 53.8 from the left sloping line toward the lower right corner.

To compute the family analytically: From the presence of 23.1 per cent quartz, the family must lie between numbers 6 and 10, since there is more than 5 per cent and less than 50 per cent quartz. Further, the ratio $\frac{\text{Or}}{\text{Ca}Naf}=\frac{18}{42}=\frac{30}{70}$, and since the orthoclase is between 5 and 35 per cent, the family belongs in No. 9.

The rock number, therefore, is 229, that is, Class 2, Order 2, Family 9.

Example 2.—A syenite having

Kf	60.0		= 76.0
$Ab_5\ An_3$	18.0		= 22.8
Qu	1.0		= 1.2
Total quarfeloids		79.0	100.0
Biot	18.0		
Hbl	2.0		
Acces	1.0		
Total mafites		21.0	
		100.0	

Percentage quarfeloids to mafites 79, therefore Class 2.

$Ab_5An_3 = Ab_{62.5}An_{37.5}$, therefore Order 2.

Quartz less than 5 per cent, therefore between Families 11 and 15.

$\frac{Kf}{CaNaf} = \frac{60}{18} = \frac{77}{23}$, therefore Family 12. The rock number is 2212; that is, Class 2, Order 2, Family 12. The values 76, 22.8, and 1.2 are used in the graphical location of the rock.

Example 3.—A nephelite-syenite with

Kf		21.5		= 39.0
$Ab_{92}An_8$	Naf	31.0		= 61.0
	Caf	2.5		
Total feldspar			55.0	100.0
Neph		27.5		
Sodal		8.5		
Total feldspathoids			36.0	
Total quarfeloids			91.0	
Aeg.-aug		5.0		
Biot		2.5		
Acces		1.5		
Total mafites			9.0	
			100.0	

Quarfeloid ratio 91. Class 2.

$Ab_{92}An_8$ . . . . Order 2.

Foids to feldspars$=\frac{36}{55}=\frac{39.5}{60.5}$. Between Families 21 and 25.

$\frac{\mathrm{Kf}}{\mathrm{Ca}Na\mathrm{f}}=\frac{21.5}{33.5}=\frac{39.0}{61.0}$. Family 23.

Rock number is 2223. The values 39 and 61 are used in plotting the rock.

Example 4—A lherzolite with

Augite	45.0	=	47.4
Hypersthene	20.0	=	21.0
Olivine	30.0	=	31.6
Hornblende	3.0		100.0
Magnetite	2.0		
	100.0		

Since there are neither feldspars, feldspathoids, nor quartz, the rock must belong in Class 4.

The ratio of ferromagnesian minerals to ores is 98 : 2, therefore the Order is 1.

The ratio of augite to hypersthene is 45:20=69:31, therefore the family lies in the middle row and is either 1, 3, 9, or 15 (Fig. 19). The ratio of augite to olivine is 45:30=60:40, and the rock again lies in the middle line including Families 2, 3, 10, and 15. The ratio of augite to hornblende is 45:3=95:6, therefore it is in the front series of families including 1, 2, 3, 4, 8, 9, 10. Family 3 is the only one common to the three computations, consequently the rock number is 413.

Graphically the rock may be plotted by using the numbers 47.4, 21.0, and 31.6.

One of the advantages of this system of classification is that each thin section of the rock may be plotted independently; the center point of all the dots representing sections from a single rock-mass will represent the average. This is much more satisfactory than estimating the average from a number of sections which differ considerably in the amounts of the constituents. The various dots representing complementary rocks will fall in straight or branching lines, showing the course of differentiation.

Before publishing his second paper on this system of classification the writer desires the opinions of more petrographers than he has been able to consult personally. *He would be very glad,*

therefore, to receive at once answers to the following questions as well as further comments from all who are interested.

QUESTIONS

1. *Classes.*—Should there be a fifth class for rocks having approximately equal amounts of light and dark constituents? The limits would then be 0–5–35–65–95–100 instead of 0–5–50–95–100, as here proposed. The introduction of an extra class would add 104 families.

2. *Orders.*—Should Order 4 (Fig. 23), in which there are very few rocks, be combined with Order 3? Order 3 would then contain all rocks with plagioclase from labradorite to anorthite inclusive. This would make the subdivisions from Ab to An at 0–5–50–100, and would reduce the number of families by 72. Of course, if the fourth order is retained the pigeonholes need not be named until rocks occupying them have been found.

3. The line separating the granites, adamellites, etc., from the corresponding quartz-rich varieties is here taken at 50 per cent quartz. Should there be a dividing line here, or should granite, for example, include all rocks having from 5 to 95 per cent of quartz? As suggested above, the division line might be made at 65, making the lines 0–5–65–95–100.

4. In the older classifications albite is united with orthoclase for the alkali rocks. This would throw out Order 1, but in the older systems, with the introduction of lime, the soda molecules are divided into two parts, and orthoclase plus albite is contrasted with the lime-soda plagioclases. This division is not logical, but is it desirable? If such a division were made, Order 1 (Fig. 20) would be dropped and the alkali rocks would form Families 1, 6, 11, 16, 21, and 26 of the triangles now representing Order 2 (Fig. 21), and soda- and potash-rocks would have to be separated in the subfamilies. The double triangle would then have orthoclase+albite +microperthite+anorthoclase for the left angle of the base, while the right corner would be Ca*Na*f, Na*Ca*f, or Caf, depending upon the orders. Such a combination would simplify the placing of rocks containing microperthite, which is worth careful consideration, but the grouping is not so correct theoretically. All of the rocks

of Fig. 20 would then fall into the dotted compartments of Fig. 21. Computed modes, however, would be more difficult to place. As a matter of fact it is usually not difficult to separate the albite in microperthite from the orthoclase. Should this change be made, Family 6, for example, would become the family of the alkali-granites, and would contain potash-granite, alkali-granite, alkali-adamellite, alkali-granodiorite, and soda-tonalite. The latter would then again become soda-granite, the first potash-granite, and the intermediate rocks soda-potash granites. Covite, mariupolite, most essexites, etc., would fall in Family 21 without differentiation. Such a combination would reduce the number of families by 72, and if the anorthite were united in Class 3, as suggested above, the total reduction would be 144 families. Personally the writer is inclined to favor separating the feldspars into the Or, Ab, and An molecules.

5. Would it be desirable to indicate, in the name of the rock itself, that the mineral proportions have been determined, and that the rock falls into a certain compartment, for example by a slight change in the spelling, such as granyt, dioryt, etc.? Of course terms like monzonite Brögger, theralite Rosenbusch, etc., might be used, but they seem cumbersome. (Granyte, dioryte, etc., cannot be used, since this spelling was suggested and used by Dana to contrast with the *-ite* endings of minerals.)

Appendix.—An alternative classification could be based upon four double tetrahedrons, representing four classes, according to the amounts of light and dark constituents, and each subdivided as in Fig. 27. The corners of the tetrahedrons would be quartz, Kf, Naf, Caf, and Foids, and the division points 0–25–75–100. There would be fewer varieties than in the preceding classification, and it would be much simpler, but the families would not correspond so closely to those in the old classifications as does the one given above.

Reviews

Geology of the Hanagita-Bremner Region of Alaska. By F. H. Moffit. U.S. Geol. Survey, Bull. No. 576. Pp. 55, figs. 6, pls. 6, maps 2.

The area described in this report is in the southern part of the Copper River drainage basin. Chitina River bounds it on the north, and it extends southward half-way to the coast.

Field work in this region was of a reconnaissance character, but the larger stratigraphic units have been outlined. The oldest sediments are mainly schists, slates, and limestones, and have been referred to the Carboniferous. These beds have been deformed by close folding and faulting and cut locally by intrusions. Unconformable above them is a series of interstratified beds of slate and graywacke thought to be equivalent to the Valdez series, and early Mesozoic in age. This series is in turn unconformable beneath conglomerates and tuffaceous slates of Middle Jurassic age.

The district presents a number of problems in physiography. The drainage has a rectilinear arrangement which must bear some close relation to geologic structure. All the valleys have been profoundly glaciated. Many streams are now eroding valley trains. A number of situations appear very favorable for stream capture.

The author is inclined to doubt the theory that Copper River is an antecedent stream across the Chucagh Mountains. He suggests that ice erosion over a narrow divide enabled a southward-flowing stream to tap the Copper River and divert it from a westward course. To complete this theory it seems necessary to assume uplift along the western part of the basin to check the flow in that direction, and that along a great part of its course the Copper River has been reversed since the retreat of the ice.

W. B. W.

The Shinumo Quadrangle. By L. F. Noble. U.S. Geol. Survey, Bull. No. 549. Pp. 100, fig. 1, pls. 18.

The remarkable geologic section exposed in the Shinumo quadrangle rivals those that have been described previously in the Grand Canyon. The generally unaltered condition of the beds, the great vertical extent

of the exposures, and the absence of a vegetal mask reveal the geologic history in great detail.

The rocks in the quadrangle range from Archean to late Paleozoic in age. The pre-Cambrian portion of the section follows:

Proterozoic
  Grand Canon series (Unkar group)
    Great unconformity

Dox sandstone	2,297	feet.
Shinumo quartzite	1,564	"
Hakatai shale	580	"
Bass limestone	335	"
Hotauta cong.	0 to 6	"

Archeozoic
    Great unconformity
      Vishnu schist

The Proterozoic sediments were deposited on a surface that represented almost perfect peneplanation. At the close of the period of deposition, uplift and great normal faulting inset these beds deeply into the Archean. This led to their preservation during the next period of great erosion, which again resulted in peneplanation by the close of the pre-Cambrian. Where not protected by faulting the Proterozoic beds were removed. The remnants are in great wedge-shaped masses, each bounded by a fault plane, and the two great erosion surfaces. In no other known region do two profound peneplains meet in a line.

Cambrian and Carboniferous sediments exist throughout the quadrangle. A disconformity represents the intervening systems. Mesozoic and Tertiary rocks ranging up to 6,000 feet in thickness formerly covered this area. In early Quaternary times a cycle of erosion, known as the "great denudation," drove their outcrops many miles to the north.

The writer follows Davis and others in recognizing but two cycles of erosion in the formation of present physiographic features. The first, the great denudation, developed a virtual peneplain, and the second, during the latter part of the Quaternary, resulted in cutting the Grand Canyon. The Esplanade and Tonto platforms, explained by Dutton as temporary base-levels, are held to be structural benches.

The writer also follows Davis in holding that the present course of the Colorado River was established before the beginning of the uplift that resulted in the canyon cycle of erosion. It is a superposed stream, let down from the surface of the peneplain of the great denudation.

W. B. W.

Gypsum Deposits of the Maritime Provinces. By WILLIAM F. JENNISON. Canada Department of Mines, No. 84, 1911. Pp. 170, figs. 19, pls. 36.

This report is largely taken up with general discussion of the world-distribution of gypsum, its origin, manufacturing processes, and the character of the manufactured products. Considerable space is given to descriptions of various local occurrences that may become of commercial importance.

Nova Scotia, New Brunswick, and the Magdalen Islands make up the Maritime Provinces. The gypsum deposits were thought at one time to belong to Permian age, but they are now known to be Mississippian. In Nova Scotia the deposits are not limited to any particular horizon, but are found near the base, in the middle of the system, and immediately underlying Pennsylvanian coal beds. They are in all cases associated with marine limestones and marls, and the author believes this fact is of great significance. The gypsum is found in beds ranging up to 100 feet thick and in many places is seen to grade into the limestone. The deposits in other provinces present no additional features of interest.

The author believes the gypsum comes from conversion of submarine limestones or marls by the action of free sulphuric acid of juvenile origin. In support of this theory he points out that numerous circular blowholes found in massive formations of the gypsum were vents for escaping gases developed by the action of sulphuric acid on the calcareous materials.

W. B. W.

Colorado Ferberite and the Wolframite Series. By F. L. HESS and W. T. SCHALLER. U.S. Geol. Survey, Bull. 583. Pp. 75, pls. 14, figs. 35.

In 1910 the Colorado field, chiefly in Boulder County, furnished approximately one-sixth of the world's production of tungsten ore. In no other field is the iron tungstate the principal ore mineral.

In the first part of the report, Hess discusses the mode of occurrence of ferberite in this district, the mineral associations being given in considerable detail. He also submits 95 out of 300 analyses examined to obtain a basis for differentiation from the remainder of the wolframite group. He proposes the following definition of the group: At one end of the series shall be placed ferberite, ranging from pure $FeWO_4$ to a composition bearing 20 per cent of the hubnerite molecule $MnWO_4$, and

at the other end shall be hubnerite in which the proportions of iron and manganese are the reverse of those given for ferberite. The term wolframite shall be reserved for mixtures of these molecules ranging between the limits assigned to the two end members.

In the latter part of the bulletin Schaller gives a detailed discussion of the crystallography of ferberite. A total of 32 forms were determined, 12 of which are new for the wolframite group.

W. B. W.

Glacier National Park. By M. R. CAMPBELL. U.S. Geol. Survey, Bull. No. 600. Pp. 54, figs. 3, pls. 13.

This bulletin is one of a series intended for popular use, now being published by the United States Geological Survey. It presupposes no knowledge of scientific geology on the part of the reader, and is intended as a guide to the chief physiographic features of the region.

The report takes up a score of the principle valleys, giving a brief statement for each regarding trails and camps, adjacent mountains, glaciers, cirques, and other physiographic features of interest. Among these is the Lewis overthrust fault. It can be observed in most of the valleys and is a controlling factor in the topography. A thick block of limestone has been thrust over shales along a fault plane dipping about 10°, for a distance averaging not less than 15 miles. The eastern boundary of the park follows closely the edge of this overthrust block.

What may be considered the culminating point of the continent is found on Triple Divide Peak. Waters falling on this peak reach Hudson Bay, the Gulf of Mexico, and the Pacific Ocean.

Geologists must regret that the scope of this bulletin was not extended by a few paragraphs on the stratigraphic column exposed in the region.

W. B. W.

Useful Minerals of the United States. By SAMUEL SANFORD and RALPH STONE. U.S. Geol. Survey, Bull. No. 585. Pp. 250.

Two lists of useful minerals in the United States were published more than twenty-five years ago in annual reports of the United States Geological Survey. Many changes in production in recent years require a new compilation and its publication in more available form.

The plan of the work includes all of the states, and under each is listed the minerals found and the more important localities. To what extent the deposits have been mined is indicated in most cases. Data

on clays, building stones, and petroleum are included also. The latter part of the report includes a glossary of more than 400 terms. Each definition of a mineral is followed by a list of the states in which it is found, so that this feature combines the features of glossary and index.

W. B. W.

Geology and Oil Prospects of Northwestern Oregon. By C. W. WASHBURNE. U.S. Geol. Survey, Bull. No. 590. Pp. 111, pl. 1.

Great development of California oil fields has led to extended prospecting in other regions bordering the Coast Range Mountains.

The sedimentary rocks exposed in this region range from Upper Eocene to Pleistocene. Shales and coarser clastics of both fresh-water and marine origin greatly predominate, intercolated with tuffs and volcanic agglomerates. Very little detailed work has been done on the stratigraphy of these systems. Fossils are quite abundant, but there are few if any remains of diatoms, so abundant in the California oil fields.

The author fails to find indications favorable for oil in this region. The structure in the northern part is a broad, low geanticline, broken by many large igneous masses, and by multitudes of small dikes and faults. That no oil exists is inferred from the fact that in all these breaks in the strata no true oil seeps have developed. Farther south, in Coos County and vicinity, the structure is essentially a broad syncline with low flanking anticlines and few dikes. The structure is favorable for oil reservoirs, but here also oil-seeps, so abundant in Mexico and Southern California, are entirely absent.

W. B. W.

Slate in the United States. By T. NELSON DALE and OTHERS. U.S. Geol. Survey, Bull. No. 586. 1914. Pp. 220, figs. 18, pls. 26.

This report is in the main a corrected and revised edition of *Bulletin* 275 issued in 1906. Since the publication of that bulletin, slates of economic value have been found in several states and additional investigation made in well-known districts.

Part I of the present bulletin summarizes the present knowledge of the origin, texture, and chemical and mineral composition of slates. The structure of slate is treated with more detail. In Part II more or less detailed descriptions are given of occurrences of slate in fourteen different

states, Pennsylvania and Vermont being treated in considerable detail. Part III takes up the problems of slate prospecting, quarrying, and the uses of slate.

Statistics for 1913 give the total value of slate production in the United States as $6,175,476. Pennsylvania produced more than one-half of the total, and Vermont more than one-fourth.

W. B. W.

Mineral Resources of Alaska. By A. H. Brooks and Others. U.S. Geol. Survey, Bull. No. 592. Pp. 413, figs. 13, pls. 17, map 1.

This bulletin is the tenth annual report upon mining conditions and mineral resources of Alaska. In addition to the administrative report there are given results of investigations in a score of districts during the 1913 field season. Several of these record the progress made in well-known mining camps, while others are results of reconnaissance trips in little-prospected districts. The more important of these preliminary reports will be embodied in separate bulletins. In these papers emphasis is laid on conclusions having immediate interest to the miner to whom a prompt publication is more valuable than a detailed report long delayed.

Gold continues to be Alaska's chief source of mineral wealth. The total production in 1913 was $15,600,000, of which 31 per cent came from lode mines and the balance from placers. The amount produced has declined rather steadily since 1906. A marked falling off in 1913 is attributed in part to unusual scarcity of water during the sluicing season. The average value recovered from placers has declined from $3.74 per cubic yard in 1908 to $1.57 in 1913.

Coal is the only mineral product that does not show a decreased output since 1912, and its production is of little consequence commercially. In connection with coal the author states: "As a rule, the quality of coal bears a direct ratio to the amount of deformation, lignite being in least-folded rocks and anthracite in those most folded."

W. B. W.

Mineral Production of Canada, for 1913. By John McLeish. Canada Dept. of Mines. Ottawa, 1914. Pp. 316.

The value of mineral products for the year amounted to more than $145,000,000, of which over $66,000,000 was in metals. Coal amounted to over $37,000,000. The remainder is distributed over a large number

of products, none of which approaches in value the amount recorded for coal.

Especial importance is attached to the quantity of products shipped from mines and works, the home consumption and the foreign trade.

A. D. B.

Proceedings of the American Mining Congress. Sixteenth Annual Session, Phoenix, Arizona, December, 1914. Denver, 1915. Pp. 239.

Contains a detailed stenographic report of the meetings, along with the text of seventeen papers and addresses presented at the session.

Most of these papers bear on the subject of mining legislation, and the broader aspects of the economics of the mining and allied industries. As usual, conservation comes in for its share of discussion.

A. D. B.

The Turquois. By JOSEPH E. POGUE. Memoirs of the National Academy of Sciences, Vol. XII, third memoir. Washington, 1915. Pp. 207, pls. 22, figs. 5.

The subtitle reads, "A Study of Its History, Mineralogy, Geology, Ethnology, Archaeology, Mythology, Folklore, and Technology."

The work is admirably adapted to the general reader as well as to the mineralogist and geologist. A large portion is devoted to the historical and ethnological study, which is of general interest. Numerous illustrations illuminate the text.

The description of all of the known producing localities is of interest to the geologist and mineralogist.

A. D. B.

Summary Report of Canadian Geological Survey. Sessional Paper 26, 1914. Pp. 201, maps 3, fig. 1.

This report contains 40 short papers by members of the staff of the Canadian Geological Survey. Each article is a brief statement of results of field work in different areas during the 1914 field season. All of these papers will be supplemented later by more detailed reports.

W. B. W.

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THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY

With the Active Collaboration of

SAMUEL W. WILLISTON, Vertebrate Paleontology
ALBERT JOHANNSEN, Petrology
STUART WELLER, Invertebrate Paleontology
ROLLIN T. CHAMBERLIN, Dynamic Geology
ALBERT D. BROKAW, Economic Geology

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ERRATA

In No. 8, 1916, of this *Journal*

P. 821, line 11, *for* Smith *read* Smyth.

P. 824, line 17, *for* stopping *read* stoping.

P. 835, line 10, *for* Riedemann *read* Ruedemann.

VOLUME XXV NUMBER 2

THE

JOURNAL OF GEOLOGY

FEBRUARY-MARCH 1917

ON THE HYPOTHESIS OF ISOSTASY

W. D. MacMILLAN
University of Chicago

The splendid papers by Hayford[1] and jointly by Hayford and Bowie[2] have brought the subject of isostasy into the foreground for discussion by geologists and others who may be interested. These papers have taken the subject out of a field of more or less vague conjecture, and by subjecting it to a very careful quantitative examination have shown very clearly that isostasy in some form can be accepted as a reality.

To be sure, they have not *proved* the reality of isostasy, for in the mathematical sense no physical hypothesis can be proven. But they have formulated precise hypotheses of isostasy and have shown that a vast mass of observational data covering the United States is very much better satisfied by theories which include their hypotheses than by the usual gravitational theory which excludes the hypothesis of isostasy.

Four distinct laws of isostasy have been discussed in these papers, viz., (*a*) uniform compensation, (*b*) uniformly decreasing

[1] John F. Hayford, *The Figure of the Earth and Isostasy from Measurements in the United States*, Publications of the U.S. Coast and Geodetic Survey, 1909.

[2] John F. Hayford and William Bowie, *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Publications of the U.S. Coast and Geodetic Survey, 1912.

compensation, (*c*) compensation in a subterranean layer, (*d*) the Chamberlin compensation. In so far as merely satisfying the observations it is found that any one of these hypotheses is as good as any other, since each of them reduces the sum of the squares of the residuals by about 90 per cent. This is a very notable reduction and it places the hypothesis of isostasy upon a solid foundation of credibility. We say "credibility" and not "proof" advisedly, for there still remains the possibility that some other hypothesis, non-isostatic in its nature, may satisfy the observations even more closely, and it is a very difficult matter to show that no such hypotheses exist.

There seems to be nothing inherently improbable in the notion that the density of the materials under the continents is less than that under the oceans. Hayford's success, which must be considered a notable one, consists in showing, by very complete computations which extend over a large mass of data, that assumptions of very moderate differences of density are sufficient to bring the observations and theory into fairly close accord. Whether or not any other hypothesis will or can be equally successful must of course be left for the future. Until some such hypothesis makes its appearance we are fairly entitled to put our faith in the broader outlines of isostasy and leave it to further observations and discussions to make the details of the theory more precise.

Notwithstanding the fact that all four of the hypotheses discussed by Hayford satisfy the observations equally well, it would seem as if Hayford prefers the hypothesis of uniform compensation to a depth of 122 kilometers and usually has this hypothesis in mind when thinking of isostasy. This preference, which does not seem to be warranted by his own discussions,[1] is somewhat dangerous in that conclusions which are peculiar to this hypothesis are given a prominence to which they are not entitled. Thus, one is

[1] Second, it is not possible to ascertain whether this compensation is more probable than the G compensation, uniformly distributed from the surface to the depth 70.67 miles, since the two sets of computed deflections agree so closely that their differences are much smaller than the accidental errors.—*The Figure of the Earth and Isostasy from Measurements in the United States*, p. 159.

A corresponding statement is made on p. 162 with respect to the Chamberlin compensation.

rather likely to gain the impression from Hayford's writings that the "depth of compensation" is in the neighborhood of 122 kilometers and that this "depth" is as well established as are the broader outlines of the theory. This is not true, for we do not know that the compensation is uniform. From the hypothesis of uniformly decreasing compensation Hayford finds the depth of compensation to be 175 kilometers, and from the "Chamberlin compensation" 286 kilometers. Clearly, the "depth of compensation" is very sensitive to change of hypothesis, and it is further clear that with a slight modification of the hypothesis the "depth of compensation" could be made to retreat to the center of the earth, or even to vanish altogether.[1] From this it is obvious that the existence of a precise depth of compensation is not an essential part of the theory of isostasy. These considerations deprive the depth of 122 kilometers of the importance or weight which constant repetition is likely to attach to it. It is still doubtful whether the term "depth of compensation" corresponds to any physical reality, however useful the idea may be in our hypotheses.

If the solid portion of the earth were altogether lacking in rigidity, and if the concentric layers were homogeneous in density, then the upper surface of the solid earth would be an oblate spheroid, and this surface would lie about 9,000 feet below the present sea-level. It would be covered uniformly by the waters of the ocean, and the pressure at any interior point would be a function of latitude and depth only, and not a function of the longitude. Let us suppose now that this solid spheroid is endowed with a certain amount of rigidity and is differentiated somewhat with respect to density, particularly in the neighborhood of the surface. If the rigidity were not too great, it seems clear that the heavy regions would be depressed by the excessive weight, and that the lighter regions would rise on account of their deficiency of weight. If the differentiation of density were sufficiently great, it is clear that the

[1] The idea implied in this definition of the phrase "depth of compensation" that the isostatic compensation is complete within some depth much less than the radius of the earth is not ordinarily expressed in the literature of the subject, but it is an idea which is difficult to avoid if the subject is studied carefully from any point of view.—Hayford and Bowie, *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, p. 10.

regions of sufficiently deficient density would eventually appear above the surface of the waters of the ocean, while the regions of greatest density would form the great depths of the basins into which the the waters of the ocean were gathered. Those regions which have neither excess nor deficiency of density would still remain about 9,000 feet below the sea-level except in so far as, through rigidity, they partook of the movement of neighboring regions. A theory of isostasy comprehending the entire earth in its grasp should therefore be based upon a level 9,000 feet below the surface of the ocean. Regions which lie above this level are deficient in density and regions which lie below this level are excessive in density. Clearly, it would not do to regard the sea-level, which from an isostatic point of view is an accidental level, as the dividing surface. Indeed, if the differentiation of density were so small that the elevated regions were all below the sea-level, we should be compelled to conclude that the density was everywhere excessive—a *reductio ad absurdum.*

But the sea-level is precisely the surface which Hayford has chosen, and, as a consequence, to all those regions which lie between the sea-level and 9,000 feet thereunder he has ascribed an excess of density instead of a deficiency. Since approximately three-quarters of the earth's surface lies under the ocean at an average depth of approximately 15,000 feet, and since under Hayford's hypotheses too great density is ascribed to this region, it would seem that his hypothesis has had the effect of raising the mean surface density for the entire earth from 2.67 to a somewhat higher figure. This alone might not be of any great importance, since at best the figure 2.67 is somewhat uncertain, but a hypothesis which is based upon sea-level gives horizontal changes of defect of density over the continents which are relatively too great, as is shown in Table I, which is based upon the hypothesis of uniform compensation.

Thus, with the sea-level basis the defect in density under a region which has an altitude of 6,000 feet is six times as great as the defect in density under a region which has an elevation of 1,000 feet, while with a true, isostatic theory the defect would be only one and one-half times as much. The defect under a 1,000-foot

elevation is twice as great as under a 500-foot elevation on the one hypothesis and only twenty-nineteenths times as great on the other. This indicates that the sea-level basis overaccentuates the importance of changes of level in the topography of the continents.

TABLE I

Elevation in Feet	Defect in Density Sea-Level Basis	Defect in Density 9,000-Foot Basis	Elevation in Feet	Defect in Density Sea-Level Basis	Defect in Density 9,000-Foot Basis
0.......	0	9	4,000......	4	13
1,000.......	1	10	5,000......	5	14
2,000.......	2	11	6,000......	6	15
3,000.......	3	12	7,000......	7	16

If the density in the earth's crust actually varies in the manner supposed by Hayford (using the sea-level basis), one would expect regions over which the compensation was effected to be smaller than if the density varies according to a true isostasy (i.e., the 9,000-feet-below-the-sea basis), since the changes in density are relatively greater in the first case than in the second. Hayford has attempted to determine the sizes of these areas of compensation, but the quantities to be considered were so small that success was scarcely to be expected; indeed, they are "frequently less than the errors of observation and computation" and, possibly, also less than the effects of local irregularities of density. The evidence, though inconclusive, leaned faintly toward rather small areas of compensation, and Hayford is of the opinion that these areas are between a square mile and a square degree.[1] If the present writer is correct in assuming that a true isostasy must be based upon a level 9,000 feet below the sea, then the evidence published by

[1] It is certain from the results of this investigation that the continent as a whole is closely compensated, and that areas as large as states are also closely compensated. It is the writer's belief that each area as large as one square degree is generally largely compensated. The writer predicts that future investigations will show that the maximum horizontal extent which a topographic feature may have and still escape compensation is between one square mile and one square degree. This prediction is based, in part, upon a consideration of the mechanics of the problem.—Hayford and Bowie, *The Effects of Topography and Isostatic Compensation upon the Intensity of Gravity*, p. 102.

Hayford and Bowie on the extremely delicate question[1] of the "areas of compensation" is not altogether trustworthy, and the sizes of these areas must be regarded as unknown.

From the fact that the hypothesis of isostasy reduced the sum of the residuals from 65,434 to 8,013, or by approximately 90 per cent, and from the fact that the average elevation of the United States is about 2,500 feet Hayford concluded that the average departure from complete isostasy in the United States is equal to about 250 feet of rocks. It is not easy to see how Hayford drew this conclusion. It certainly has no mathematical justification, for even if the theory were perfect and the isostasy complete, the sum of the squares of the residuals would not be zero, since the imperfections of the observations would still give us a very respectable, but quite unknown, sum. How then can we form a quanti-

[1] If the separate anomalies in the United States be compared, it is found that in 16 cases out of 41 the anomaly with local compensation assumed is smaller than with regional compensation assumed uniformly distributed to zone K (18.8 kilometers), and only 13 cases in which it is larger. Similarly, there are 20 cases out of 41 in which the anomaly with local compensation is smaller than with regional compensation extending to zone M (58.8 kilometers), and only 15 cases in which it is larger. There are 26 cases out of 41 in which the anomaly with local compensation assumed is smaller than with regional compensation assumed to extend to zone O (166.7 kilometers), and only 12 cases in which it is larger. In all other cases the two anomalies compared are identical to the last decimal place used, the third.

The evidence either for or against local compensation in comparison with such regional compensation distributed uniformly over these moderate distances is necessarily slight and possibly inconclusive. For, as shown in the table, the difference between computed effects of compensation in the two cases compared is very small upon an average. The whole evidence is furnished by these very small differences, which frequently are less than the errors of observation and computation. As shown by the table, there is but one station among the 41—namely, No. 43, Pike's Peak—at which the difference between the computed effect of local compensation and the computed effect of regional compensation uniformly distributed to zone K exceeds 0.004. Such a difference tends to become greater as the distance over which the regional compensation is supposed to be uniformly distributed is increased, but columns 7 and 8 of the table show that even when the regional compensation is assumed to extend to zone O, a distance of 166.7 kilometers, from the station, there is only one station among the 41—namely, station no. 54, San Francisco—at which the computed effect of local compensation and the computed effect of regional compensation exceeds 0.017 dyne.

Nevertheless the evidence, slight as it necessarily is, indicates that the assumption of local compensation is nearer the truth than the assumption of regional compensation uniformly distributed to zone K (18.8 kilometers). The evidence is still stronger in the same direction when the comparison is made between local compensation and regional compensation extending uniformly to the greater distances, 58.8 and 166.7 kilometers, represented by zones M and O.—Hayford and Bowie, *The Effects of Topography and Isostatic Compensation upon the Intensity of Gravity*, p. 101.

tative judgment from the sum of the squares of the residuals which depends, not only upon the imperfections of the theory, but upon the imperfections of the observations as well? Obviously, it cannot be done. The estimate of 250 feet is little more than a guess, however shrewd the guess may be. If we use the 9,000-foot level as the basis of our guess, then the average elevation of the United States is 11,500 feet, and the average departure from complete isostasy is 1,150 feet of rocks instead of 250 feet. It would not be altogether fair, however, to make this direct substitution, for the reduction of the sum of the squares of the residuals from 65,434 to 8,013 was accomplished on the sea-level hypothesis, and the reduction might be quite different under another hypothesis.

From a purely mathematical point of view, any set of a finite number of observations of the intensity and direction of gravity can be satisfied, not approximately, but exactly, in infinitely many ways by a proper distribution of density in the earth. The virtue of the theory of isostasy, therefore, lies, not in the mere fact that the observations are more nearly satisfied by the theory than without it, but in the fact that a definite principle is laid down for the variations of density, and that this principle brings theory and observations into a satisfactory accord. As Hayford's four distinct hypotheses show, any smoothly uniform hypothesis of isostasy can be regarded only as a first approximation to the actual situation, and Hayford has been successful in showing that any one of these four hypotheses is a good first approximation. It is equally clear that such delicate points as "depth of compensation" and size of "areas of compensation" depend for their successful determination upon the vastly more difficult matter of second and higher approximations, and these approximations can be obtained, if at all, only by a very much more dense net of observations, and quite likely the observations themselves would have to be still further refined.

While the theory of isostasy has made a very successful approach to the solution of the problem of bringing the anomalies of observation into accord with the theory of gravity, it must be admitted that there is no evidence to show that the solution of the problem is necessarily isostatic.

THE MIDDLE PALEOZOIC STRATIGRAPHY OF THE CENTRAL ROCKY MOUNTAIN REGION[1]

C. W. TOMLINSON
University of Chicago

CONTENTS

PART I

PART II

[1] An abridgment of a thesis presented for the degree of Doctor of Philosophy at the University of Chicago, 1916.

PART I

FOREWORD

This paper is the result of three months' field work by the writer in the central Rocky Mountain region during the summer of 1915, under the auspices of the University of Chicago. For assistance in planning the field investigation the writer is indebted to Dr. Eliot Blackwelder, of the University of Wisconsin, and to Dr. R. D. Salisbury, of the University of Chicago; for aid in the identification of fossils, to Dr. Stuart Weller, of the University of Chicago; and for helpful suggestions and criticism of the material of the thesis, to all of these gentlemen.

The problem centered about several broad gaps in the existing knowledge of the Ordovician, Silurian, and Devonian history of western Wyoming and adjacent parts of neighboring states; for example: (1) the "Jefferson limestone" of the Absaroka Range, of Yellowstone National Park, and of southwestern Montana was known to be in part Devonian, but the presence of Ordovician and Silurian strata within this formation and its relation to the Bighorn dolomite of central and north-central Wyoming were matters of dispute; (2) hiatuses were suspected at the base and at the top of the Ordovician-to-Devonian sequence of this region, and at more than one horizon within that sequence, but no physical evidence of any such hiatus ever had been cited; (3) the relation of the Wyoming Ordovician and Upper Cambrian to the corresponding systems in northeastern Utah had never been studied by careful stratigraphic comparison; and (4) the relation of the Silurian to the Ordovician in northeastern Utah was unknown.

By first-hand studies, in one season, of ten complete, and in most cases excellently exposed, sections at strategic localities scattered throughout the area involved, the writer is enabled to throw considerable new light upon all of these questions.

Because of the well-known scarcity of fossils in the strata which were to form the subject of his investigation, the writer set out with intent to make the greatest possible use of correlation by means of lithologic characters. To this end he made accurate measurements and described in detail, in every section, each member of the sequence which could be distinguished from other members by its lithological characters. Collections of fossils, although made secondary to the work of lithological description and measurement, and in no case exhaustive, were made wherever opportunity presented itself, and in each case served to corroborate the correlation which otherwise would have been made on the basis of lithology alone. For instance, the presence of the Ordovician Bighorn dolomite as the thick basal member of the so-called "Jefferson limestone" in the areas of the Absaroka, Wyoming (No. 52), and Livingston, Montana (No. 1), folios was established beyond doubt by both lines of evidence, though it would have been well established by either one alone.

In these correlations it was realized that the coincidence of the lithological characters of a single member at one locality with those of one member in the same stratigraphic position in another locality is much more inconclusive (although significant) than the correspondence of several successive members in one section to the same number of members occurring in the same order and in the same stratigraphic position in another. In nearly every case where a single bed in one section was found to correspond accurately in character to one bed in another section, not less than two other contiguous members were found to correspond in like manner. Where several members of one section appeared to be missing from another section, a hiatus was inferred in the latter; and such inference was substantiated in several cases by more direct evidence at the suspected horizon.

LOCATIONS OF SECTIONS MEASURED, 1915

(See map, Fig. 1)

I. (Partial.) In the northwest wall of the canyon of Big Goose Creek, about 20 miles southwest of Sheridan, Wyoming.

II. *Goose Creek Ridge.*—On the crest of the "limestone front ridge" on the northeast flank of the Bighorn Range, between Big and Little Goose creeks, about 20 miles southwest of Sheridan, Wyoming.

III. *Cody, Rattlesnake Mountain.*—On the southwest angle of Rattlesnake Mountain, north of Shoshone Dam, 9 miles west of Cody, Wyoming.

IV. *Dead Indian Creek.*—On the nose of the main ridge running parallel to the valley of Dead Indian Creek on the southeast side thereof, just south-

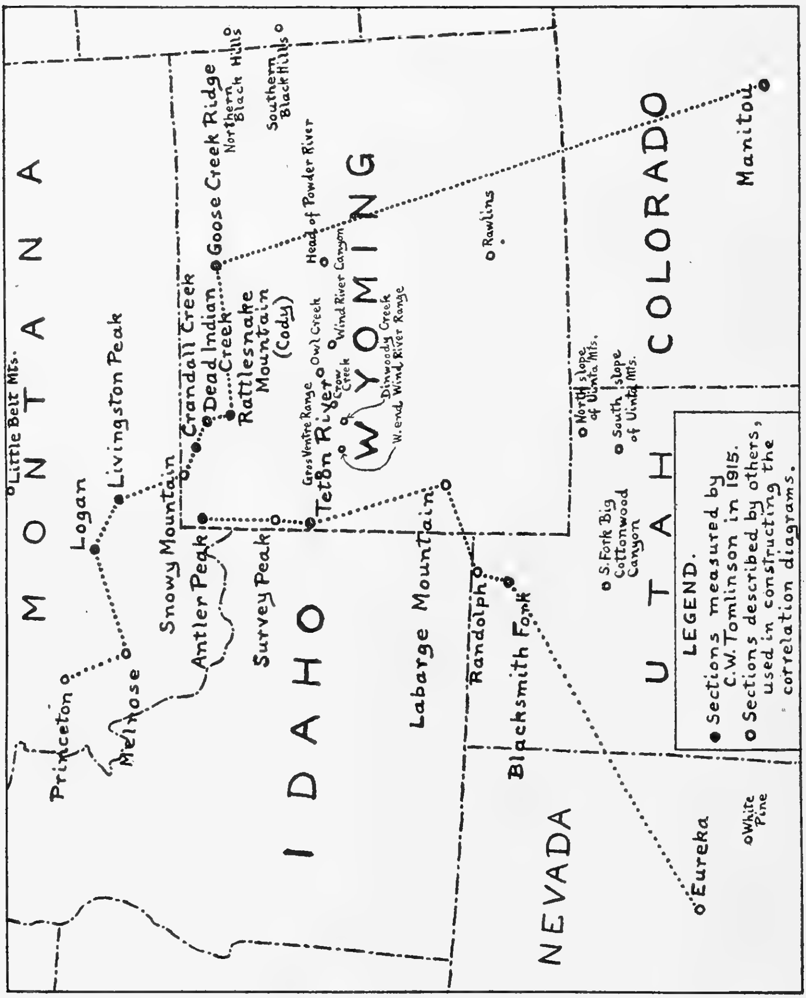

Fig. 1.—Map showing localities referred to in this paper

west of the crossing of the road from Cody to Sunlight Basin, Wyoming, a few miles east of the east border of the Crandall quadrangle.

V. *Crandall Creek.*—At the west end of the north slope of Windy Mountain, in the south wall of the valley of Clark Fork, near the mouth of Crandall Creek, in the Crandall quadrangle (Absaroka Folio), Wyoming.

VI. (Incomplete.) *Antler Peak,* Gallatin Range, Yellowstone Park, Wyoming.

VII. (Cambrian only.) On the ridge running west from the summit of Livingston Peak, Livingston quadrangle, Montana, about one mile north of "Old Baldy."

VIII. *Livingston Peak.*—On the south slope of Livingston Peak, on the ridge leading to "Old Baldy" (the 9,500-foot peak 1 mile southwest of Livingston Peak), Livingston quadrangle, Montana.

IX. *Logan, Montana.*—On the ridges north of the Gallatin River, opposite Logan, in the Three Forks quadrangle, Montana.

X. *Teton River.*—On the divide between Teton River and South Leigh Creek, Grand Teton quadrangle, Wyoming.

XI. *Blacksmith Fork* (including the Cambrian).—Measured across the ridges just north of the canyon of Blacksmith Fork, Cache County, Utah, from Cottonwood Gulch to the crest of Logan Peak, west of Saddle Creek.

XII. *Manitou.*—Measured on the ridges from one to two miles northwest of Manitou, Colorado.

STRATIGRAPHY

THE CORRELATION DIAGRAMS

Use of the diagrams.—Detailed descriptions of the 12 sections above listed cannot be printed here. A consistent application of the principles of correlation outlined on pp. 115, 122, however, has made it possible to formulate a standard list of members. Each of the 12 sections is made up of a part or all of the members in this list (see pp. 123–28), and includes no others. By combining these members in the manner indicated by the accompanying correlation tables (Figs. 2, 3) and diagrams (Figs. 4, 5), every one of the 17 stratigraphic sections used in the compilation of the list can be reconstructed. For instance, the Devonian system in the Crandall Creek section is made up of Member 1, with a thickness of 47 feet, overlain by Member 2, 26 feet thick, which is followed by Member 3, 28 feet thick, and so forth. Even if some of the strata in a given section be erroneously placed in the correlation table, yet the table and the standard list of members will furnish a correct description of that section, with accurate measurements of its constituent parts.

The description of each member is given in considerable detail, but is sufficiently generalized in each case to cover all observed variations in character from place to place. In the few cases where

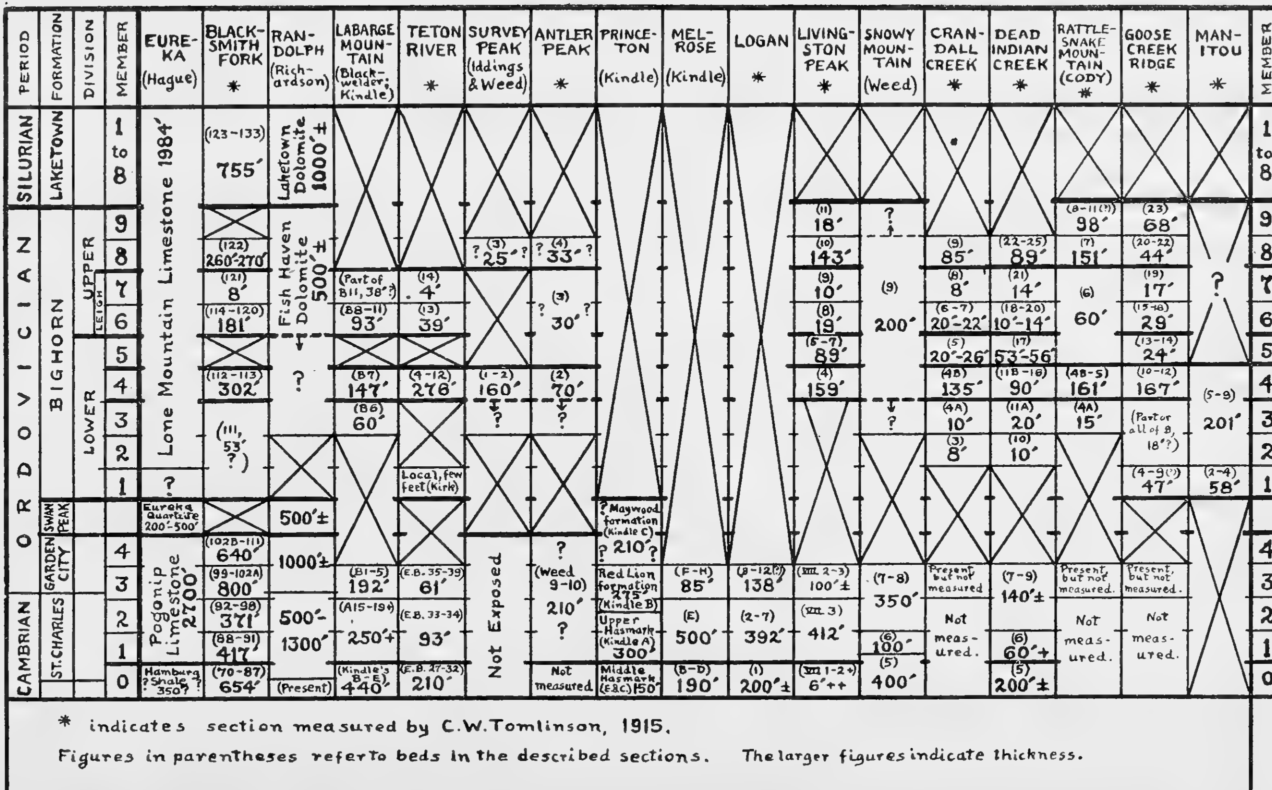

FIG. 2.—Correlation table for the Cambrian, Ordovician, and Silurian systems

Period	Formation	Division	Member	Eureka (Hague)	Blacksmith Fork *	Randolph (Richardson)	Labarge Mountain (Blackwelder)	Teton River *	Survey Peak (Iddings & Weed)	Antler Peak *	Princeton (Kindle)	Melrose (Kindle)	Logan *	Livingston Peak *	Snowy Mountain (Weed)	Crandall Creek *	Dead Indian Creek *	Rattlesnake Mountain (Cody) *	Goose Creek Ridge *	Manitou *	Member
Mississippian	Madison		3		(153+)	600'-	(B35-46)	(EB110-140) 750'±	(12-16) 1300'±	(I.&W. 22-31+) 610'+	(E.&C.)	(K+)	(Peale)	(Hague)	(Not measured)	(Hague)	(Not measured)	(Fisher)	(Darton)	Millsap	3
			2		2,000'+	1600'	750'	(EB102-109) 142'	(11) 300'	(I.&W. 21) 50'	1200'- 1500'	300'+	1200'- 1500'	1800'	(16) 150'	1600'±	(42-43+) 80'++	600'- 700'	1000'±	Limestone	2
			1	?						(I.&W. 20) 100'				(23) 180'	(15) 175'					150'±	1
←?→	Three Forks		21		(150-152) 197'								(Haynes 1-3) 110'		?	(56-61) 67'	(36-41) 49'				21
			20		(145-149)								(Haynes 4-5) 130'								20
			19		781'	200'±	(B34) 115'	(42-43A) 68'	?			(J) 200'±	(Haynes 6-7) 105'	(21) 80'		(54-55) 54'	(33-35) 44'	? (13) ? 109'	? (25-37) ? 238'		19
Devonian	Jefferson	Upper	18		(143B-144) 136'		(B33) 76'	(41) 51'					(26-27) 68'	(20) 62'	(14) 200'	(53) 28'		(12, 51 ???)	(24, 30 ???)		18
			17		(142-143A)		(B30-32)	(37-40) 58'	(6-10) 125'					(19) 85'		(48-52) 64'					17
			16	Nevada Limestone 5000'±	134'	Jefferson Dolomite 1200'±	136'	(33-36) 22'		(I.&W. 19) 40'			(25) 190'		(13, 20'?)						16
			15				(B28-29) 19'	(28-32) 51'							(12, 25'?)						15
		Main	14		(141) 93'		(B25-27) 160'														14
			13		(140) 65'		(B24) 54'				(D)	(I)	?		?						13
			12		(139) 60'		(B23) 72'														12
			11				(B17-22)				800'	500'±									11
			10				304'			(15) 75'			(13-24)	(18)		(44-47)	(32)				10
			9		(135-138)			(27) 3'	(5) 100'	(11-14) 28'			312'	209'		47'	233'				9
			8					(24-26) 17'		(9-10) 31'					(11)	(42-43) 16'					8
			7		533'		(B14-16)	(23)		(8)					150'	(38-41) 11'	(31)				7
			6				81'	37'		19'			(Part of 12, 50'?)	(16-17) 43'			14'				6
			5					(22) 17'	?	(7) 8'							(30) 23'				5
			4				(B13) 10'	(20B-21) 4'								(38, 1' is of this type)					4
		Basal	3				(B12) 95'	(18-20A) 28'						(14-15) 14'		(35-37) 28'					3
?			2	(Part of Lone Mountain Limestone?)	(134) 202'	(Part of Laketown Dolomite ?)	(Part of B11, 38'?)	(15) 23'	(4) 10'	(5-6) 23'	?	?	?	(12-13) 21'	(10) 20'	(32-34) 26'	(27-29) 5'				2
			1		(Part of 133?)											(10-31) 47'	(26) 3'				1

FIG. 3.—Correlation table for the Devonian system

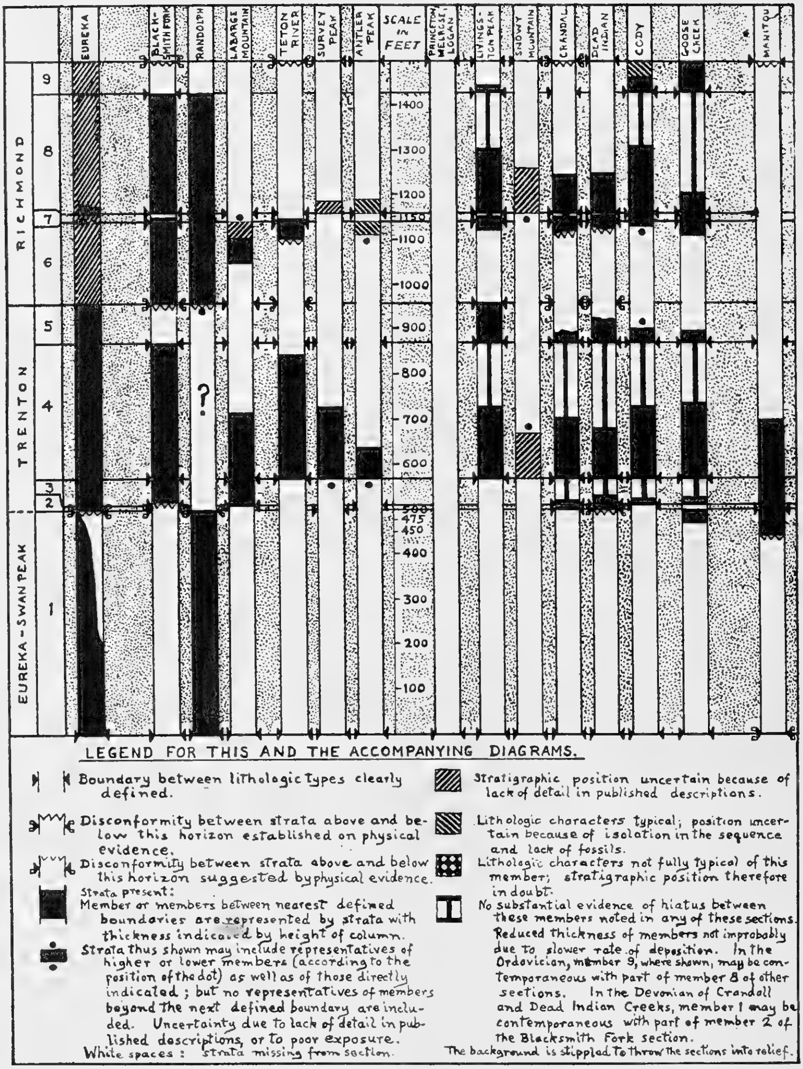

FIG. 4.—Correlation diagram for the Ordovician system, drawn to scale

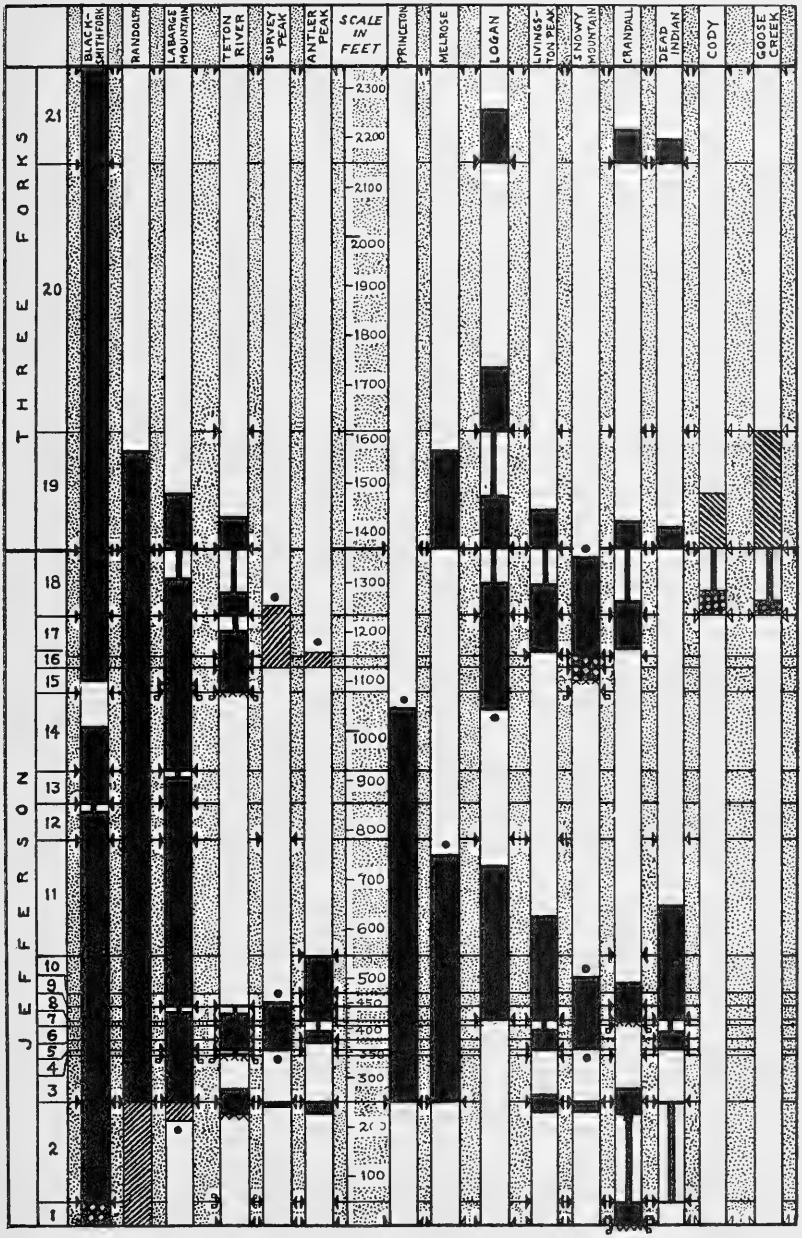

FIG. 5.—Correlation diagram for the Devonian system, drawn to scale

such variations are conspicuous or important they are specifically described for the locality where they were noted.

The standard list of members, together with the detailed correlation tables (Figs. 2, 3), in effect furnishes a compound section for 17 different localities in the central Rocky Mountain region.

Method of correlation.—In making the correlations here set forth the notes and the specimens from each section were carefully compared with the notes and the specimens from every other section, at first singly, then in groups. When a thorough and comprehensive tentative plan of correlation had been completed, all of the specimens from all the sections were laid out on a specially prepared floor, marked off into intersecting columns and rows, so that comparison of all the specimens thought to belong to a given horizon could be made at once, and at the same time all possible alterations in the proposed plan of correlation could be considered with the specimens in view. Happily, the original plan stood the test with very few changes, and those were of minor consequence.

All available paleontological data were carefully studied to determine as accurately as possible the age of the several members.

This correlation is not to be considered as final in all details, and even a few of its larger features are still clouded by uncertainty due to lack of data. The points in doubt are indicated in the diagrams and discussed in the pages following.

Sources of data.—The 7 sections, other than those measured by the writer, which are embodied in the correlation were taken from the following sources:

Eureka District, Nevada.—Arnold Hague, "Geology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs,* XX (1892).

Randolph quadrangle, Utah.—G. B. Richardson, "The Paleozoic Section in Northern Utah," *Amer. Jour. Sci.*, 4th Ser., XXXVI (1913), 406–18.

Labarge Mountain, Wyoming.—Eliot Blackwelder, unpublished manuscripts, *U.S. Geol. Survey;* E. M. Kindle, "The Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bull. Amer. Pal.*, IV, No. 20 (1908), 12–13.

Survey Peak, Wyoming.—J. P. Iddings and W. H. Weed, "Descriptive Geology of the Northern End of the Teton Range," *U.S. Geol. Survey, Monographs,* XXXII, Part 2 (1899), chap. iv, p. 180.

Princeton, Montana.—E. M. Kindle, *op. cit.*, p. 10.

Melrose, Montana.—E. M. Kindle, *op. cit.*, p. 9.

Snowy Mountain, Wyoming.—W. H. Weed, "Geology of the Southern End of the Snowy Range," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. vi, pp. 206, 213–14.

With the exception of Blackwelder's section at Labarge Mountain none of these was described in detail, and the correlation given for them is of necessity very general and subject to thoroughgoing revision.

Additional data on the thickness of Cambrian and Mississippian members were secured from the following sources:

Teton River, Wyoming.—Eliot Blackwelder, unpublished manuscripts, *U.S. Geol. Survey.*

Antler Peak, Wyoming.—J. P. Iddings and W. H. Weed, "Descriptive Geology of the Gallatin Mountains," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. i, p. 22.

Logan, Montana.—A. C. Peale, "Description of the Three Forks (Montana) Sheet," *Geol. Atlas U.S.*, Folio 24 (1896).

Livingston Peak, Montana.—Arnold Hague, "Description of the Livingston (Montana) Sheet," *Geol. Atlas U.S.*, Folio 1 (1894).

Crandall Creek, Wyoming.—Arnold Hague, "Description of the Absaroka Quadrangle," *Geol. Atlas U.S.*, Folio 52 (1899).

Rattlesnake Mountain, Wyoming.—C. A. Fisher, "Geology and Water Resources of the Bighorn Basin, Wyoming," *U.S. Geol. Survey, Prof. Paper No. 53* (1906), p. 14.

Goose Creek Ridge, Wyoming.—N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.*, Folio 141 (1906).

Princeton, Montana.—W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Survey, Prof. Paper No. 78* (1913).

Data concerning the Three Forks formation near Logan, Montana, were taken from:

W. P. Haynes, "The Fauna of the Upper Devonian in Montana, Part 2, The Stratigraphy and the Brachiopoda," *Annals of the Carnegie Museum*, X (1916), 16–17.

STANDARD LIST OF MEMBERS

Constituting the Middle Paleozoic Section in Western Wyoming, Southwestern Montana, and Northeastern Utah

(M.T. = Maximum thickness known in this region)

MISSISSIPPIAN

3. Main body of the Madison limestone. Interbedded massive and flaggy limestones, blue-gray, gray, brown, or black, crystalline to dense, with some layers abundantly fossiliferous. Chert of local occurrence only. M.T.,

2,000 feet, more or less, in Utah. 1,500 feet in the Livingston quadrangle, Montana.

2. Coarsely crystalline, very fossiliferous limestone, free from chert. M.T., 150 feet, Snowy Mountain section, Yellowstone Park.

1. Very hard, cherty, black or gray limestone. Fossils few or fragmentary. M.T., 175 feet, Snowy Mountain. (Members 1 and 2 of the Mississippian are differentiated from Member 3 only in Yellowstone Park and vicinity.)

DEVONIAN

(Member 21 may prove to be of Mississippian age; Members 1 and 2 may be Silurian.)

Three Forks Formation

(M.T., 978 feet, Blacksmith Fork)

21 (=Haynes's 1, 2, and 3). Thin-bedded or papery black shales, overlain by yellow or reddish sandstones, sandy shales, or arenaceous limestones. M.T., 197 feet, Blacksmith Fork.

. . . . Break in Sedimentation . . . .

20B. Blue-gray platy or nodular limestone. M.T., 361 feet, Blacksmith Fork (Beds 146B–149).

20. (=Haynes's 4 and 5). Fissile green shale, capped by nodular gray limestone, both very fossiliferous; the horizon of the *Clymenia* fauna in Montana. 130 feet, Logan, Montana. M.T., of Members 19 and 20 together, 420 feet, Blacksmith Fork (Beds 146–146A).

19. (=Haynes's 6 and 7). Orange-yellow to reddish platy limestones and calcareous shales (drab to cream or yellow on fresh surfaces). 109 feet, Logan (238 feet, Goose Creek Ridge).

Upper Division of the Jefferson Dolomite

(M.T., 270 feet, Blacksmith Fork)

18. Brecciated ($\frac{1}{4}$-inch to $\frac{3}{4}$-inch fragments) drab to gray-brown, massive dolomite, in most places forming cliffs. M.T., 136 feet, Blacksmith Fork.

17. Drab, yellow, and buff to dark-brown, thin-bedded limestones or dolomites, locally in part shaly. M.T., 85 feet, Livingston Peak.

16. Moderately massive dolomite, gray to brown, with rough surface. Sparingly fossiliferous in Yellowstone Park. M.T., 40 feet, Antler Peak (Iddings and Weed).

15. White or variegated sandstone, locally represented by light-gray dolomite full of coarse quartz grains, or by limestone conglomerate(?) (Snowy Mountain). In the Teton River section, interbedded with dark-brown,

pitted dolomite, probably representing part of Member 16. 19 feet, Labarge Mountain; 51 feet total, Teton River.

. . . . Break in Sedimentation . . . .

Main Division of the Jefferson Dolomite

(M.T., 681 feet, Labarge Mountain)

14. Imperfectly exposed. Ledges of fine-grained, brown dolomite. Float of thin-bedded, drab and buff dolomite also. M.T., 160 feet, Labarge Mountain.
13. Cliff-making, steel-gray or gray-brown, fine-grained, calcitic, pitted dolomite. M.T., 65 feet, Blacksmith Fork.
12. Very poorly exposed. Float of thin-bedded, light-gray and buff dolomite, very calcitic, grayish-brown dolomite, and calcareous shale. M.T., 72 feet, Labarge Mountain.

8–11. Main body of the Jefferson dolomite in Wyoming and Montana. Blackish to light-brown and brownish-gray, thick-bedded dolomite, weathering to brown-gray or gray. Very fetid odor on fresh fracture. Characteristically with a rough weathered surface. Locally calcitic, or with some layers mottled and streaked with buff. Locally quite fossiliferous at certain horizons. 312 feet, Logan; probably somewhat more at Labarge Mountain and at Blacksmith Fork.

10. (Differentiated at Antler Peak only.) Brown and drab to whitish dolomite with yellow-brown bands. M.T., 75 feet, Antler Peak.

9. Dark-brown, saccharoidal, fetid dolomite, with rough weathered surface. M.T., 28 feet, Antler Peak.

8B. White, drab, or pearl-gray dolomite, conspicuous because of its light color. M.T., Labarge Mountain (Bed 16), 3 feet; Teton River (Bed 26), 1 foot 6 inches; Antler Peak (Bed 10), 3 feet; Crandall Creek (Bed 43), 2 feet 6 inches.

8A. Light-brown to blackish-brown, fine-grained dolomite. M.T., 28 feet, Antler Peak.

6–7. Dense to finely crystalline, white, cream, or pale-gray dolomite, platy to blocky. M.T., 37 feet, Teton River. In the Crandall Creek section sedimentation appears to have recommenced with Member 7 after an interval of nondeposition.

5. Fine-grained or saccharoidal, dark-brown, fetid dolomite, with irregular, pitted, weathered surfaces. M.T., 23 feet, Dead Indian Creek.

4. White friable sandstone at Labarge Mountain, elsewhere represented, like Member 15, by a bed of quartz grains more or less closely packed together in a matrix of white or yellowish dolomite. M.T., 10 feet, Labarge Mountain.

. . . . Break in Sedimentation (?) . . . .

Basal Division of the Jefferson Dolomite

(M.T. for Wyoming, 101 feet, Crandall Creek)

3. Fetid, dark-brown, saccharoidal dolomite, mostly thin-bedded. M.T., 95 feet, Labarge Mountain.
2. White, light-drab, or very pale lavender, dense or finely crystalline dolomite, breaking up into small, sharply angular talus. Locally carries ostracods. M.T., 202 feet, Blacksmith Fork. (Probably included with the Silurian by Kindle and Richardson in Utah because of its light color. Possibly of Silurian age.) Lies directly on the Ordovician in many sections, locally with marked disconformity.
1. (Typically developed in the Crandall Creek section only.) Thin-bedded, greatly variegated dolomite, with thin bands of red shale and black chert. Dolomites saccharoidal to very dense and closely laminated. Thin limestone conglomerate at the base. Lies directly upon the Ordovician at Crandall Creek. M.T., 47 feet, Crandall Creek.

. . . . Break in Sedimentation . . . .

(In Wyoming and Montana; not in Utah?)

SILURIAN

(Not known in Wyoming, Montana, or Colorado; typically developed at Blacksmith Fork, Utah, where it includes the following members:)

8. Massive, brown-gray dolomite, medium finely crystalline, with rough weathered surface. 190 feet.
7. Thin-bedded, slabby limestone. 5 feet.
6. Massive, pearl-gray or whitish limestone, medium finely crystalline, with hackly talus; lower 45 feet contains abundant nodules of snow-white chert like Member 5. 140 feet.
5. Massive white chert, with many quartz geodes. 10 feet.
4. Extremely massive, cream-colored, coarsely crystalline dolomite. Upper 20 feet contains much chert like Member 5. Basal 5 feet full of internal casts of a Pentamerid shell. 145 feet.
3. Massive, cream-colored or brownish dolomite, medium fine-grained, weathering to smooth surfaces. 15 feet.
2. Like Member 8. 138 feet.
1. Like Member 4. Basal 20 feet crowded with casts of Pentamerids and corals. 112 feet.

. . . . Marked Disconformity . . . .

MIDDLE AND UPPER ORDOVICIAN

Richmond (Upper Bighorn, Upper Fish Haven)

9. White to light-gray or buffish, dense to coarsely crystalline dolomite, mostly thin-bedded. Less resistant than Member 8. Cherty and very fossiliferous at Goose Creek Ridge. M.T., 68 feet, Goose Creek Ridge.

8. Cliff-making, massive dolomite, locally with algal structure. Light-buff to brownish (dark-brown at Blacksmith Fork). In the Absaroka Range, partly brecciated, mottled, brownish fragments in buff matrix. Sparingly fossiliferous at Goose Creek Ridge. M.T., 270 feet, Blacksmith Fork.
7. White to dark-drab or brown-gray, dense dolomite. Weak, breaking to small angular fragments. Locally carries ostracods. M.T., 17 feet, Goose Creek Ridge.
6. Basal dolomitic breccia or conglomerate (not seen in Goose Creek Ridge section), interleaving with, and giving place upward to, a massive, brown-gray dolomite containing much calcite in seams and geodes, or to white or drab, finely crystalline dolomite somewhat similar to Member 5. The white dolomite carries corals at Goose Creek Ridge. M.T., 181 feet, Blacksmith Fork, where the two types of dolomite above described occur interbedded.

Trenton (Lower Bighorn)

5. Typically white, almost chalky, fine-grained dolomite, breaking into small angular fragments with relatively smooth weathered surfaces. At Livingston Peak interbedded with more coarsely crystalline, brownish dolomite. Locally carries ostracods. 56 feet, Dead Indian Creek (typical throughout). M.T., 89 feet, Livingston Peak.
4. Cliff-making, massive (rarely slabby), white to light-gray or light-buff dolomite, medium to very coarsely crystalline, in many places in part with brecciated structure. Sparingly fossiliferous in many localities. 147 feet, Labarge Mountain. M.T., 153 feet, Blacksmith Fork, where it is underlain by 149 feet of massive, dark-brown dolomite, medium finely crystalline, with many seams of calcite (both members included under Member 4 in the diagrams).
3. Like Member 4, but thin-bedded or closely jointed, weak. M.T., 60 feet, Labarge Mountain.
2. (Recognized in the Crandall Creek and Dead Indian Creek sections only.) Cream to buff, finely crystalline dolomite in 2-foot beds. Fossiliferous. M.T., 10 feet, Dead Indian Creek.
1. In Wyoming, developed as a white to buff or rose sandstone, mostly soft and friable; fossiliferous, locally with fish remains. 29 feet (plus?), Goose Creek Ridge. Correlated with the Harding sandstone of Colorado. At Manitou, very arkosic, and in part deeply stained (red and green); 47 feet thick. Possibly contemporaneous with part of the Swan Peak quartzite. Possibly of Black River rather than Trenton age.

. . . . Marked Disconformity . . . .

Swan Peak Quartzite

Five hundred feet thick, in the Randolph quadrangle, northern Utah. Geneva sandstone or quartzite, north end of the Wasatch Mountains, Utah. Eureka quartzite, 200 to 500 feet thick, east-central Nevada.

UPPER CAMBRIAN AND EARLY ORDOVICIAN

4. (Known at Blacksmith Fork only.) 640 feet. Includes the following types, in descending order:

   Thin-bedded, light-gray, finely crystalline dolomite; in the upper part interbedded with olive shales and very fossiliferous. 206 feet. (Beekmantown.)

   Fossiliferous, dark blue-gray or blue-black, very finely crystalline dolomite with much black chert throughout, and a 30-foot bed of black chert at the base. 156 feet. (Beekmantown.)

   Brownish-gray to bluish-gray, finely to coarsely crystalline dolomite in 1-foot to 5-foot beds. 278 feet.

3. Mostly thin-bedded to shaly, bluish-gray to brownish-gray, finely crystalline dolomite and dolomitic shale, with many layers of *flat-pebble limestone conglomerate.* In part fossiliferous. M.T., 800 feet, Blacksmith Fork (lower 190 feet, Upper Cambrian, placed in the St. Charles formation by Walcott; remainder Ordovician). This member is represented throughout northern and western Wyoming and southwestern Montana.

2. (Not differentiated except at Blacksmith Fork.) Finely to coarsely crystalline, gray dolomite, mostly thin-bedded, weak; in part oolitic. 349 feet, Blacksmith Fork.

1. Very massive, cliff-making, coarsely crystalline white dolomite, interbedded near the top and bottom with minor beds of thinner-bedded gray dolomite. M.T., 412 feet, Livingston Peak.

0. Mostly thin-bedded, white to light- and dark-gray, finely to coarsely crystalline dolomite, locally with much sandstone in lower part, and with interbedded flat-pebble limestone conglomerate. In part fossiliferous. Lower (barren) half called Middle Cambrian by Walcott at Blacksmith Fork (upper part of the Nounan formation). M.T., 654 feet, Blacksmith Fork.

PALEONTOLOGICAL COLLECTIONS: ASSEMBLED LISTS

DEVONIAN

Members 5–11:

Actinostroma sp. Antler peak, Livingston Peak.
Alveolites goldfussi Billings. Livingston Peak.
Anplexus cf. *hamiltoniae* Hall. Antler Peak.
Blothrophyllum(?) cf. *cinctutum* Davis. Antler Peak.
Zaphrentis(?) sp. Livingston Peak.
Atrypa missouriensis Miller. Livingston Peak.
Bryozoa. Antler Peak, Livingston Peak (2 sp.).

Member 3:

Atrypa missouriensis Miller (fragmentary). Teton River.

Member 2:

Unidentifiable brachiopod and gastropod fragments. Teton River.
Leperditia sp. Livingston Peak, Teton River (2 sp.).

SILURIAN (BLACKSMITH FORK ONLY)

Member 8, 10 feet below top:
Syringopora cf. *verticillata* Goldfuss.

Member 4, base:
Favosites sp.
Zaphrentis(?) sp.
Conchidium knighti Sowerby.
Pentamerus cf. *oblongus* Sowerby.

Member 2:
Syringopora sp.

Member 1:
Favosites sp.
Conchidium knighti Sowerby.
Pentamerus cf. *oblongus* Sowerby.

UPPER ORDOVICIAN (RICHMOND)

Member 9. (Goose Creek Ridge only.)
Calapoecia(?) cf. *anticostiensis* Billings.
C. cribriformis (Nicholson).
Favosites (n.sp.?).
Halysites gracilis (Hall).
Streptelasma sp.
Crinoid fragments.
Rhynchotrema sp.
Zygospira modesta(?) Hall
Orthoceras(?) sp.
Bryozoa.

Member 8:
Calapoecia sp. Blacksmith Fork.
Streptelasma sp. Goose Creek Ridge, Blacksmith Fork.
Dalmanella cf. *testudinaria* (Hall) and *hamburgensis* (Walcott). Goose Creek Ridge.
Orthoceras(?) sp. Goose Creek Ridge.

Member 7:
Crinoid fragments. Dead Indian Creek.
Dalmenella(?) sp. Crandall Creek, Teton River(?).
Leperditia sp. Goose Creek Ridge, Crandall Creek, Teton River.

Member 6:
Calapoecia(?) cf. *anticostiensis* Billings. Goose Creek Ridge.
Columnaria sp. Dead Indian Creek.
Halysites gracilis (Hall). Goose Creek Ridge.
Cf. *Protarea richmondensis* Foerste. Goose Creek Ridge.
Streptelasma sp. Goose Creek Ridge.
Pachydictya fenestelliformis(?) Nicholson. Goose Creek Ridge.
Rhinidictya cf. *mutabilis* (Ulrich). Goose Creek Ridge.

MIDDLE ORDOVICIAN

Member 4:

Spheroidal algae. Teton River.
Receptaculites oweni Hall. Livingston Peak.
Lichenaria cf. *typa* Winchell and Schuchert. Rattlesnake Mountain.
Columnaria alveolata Goldfuss. Rattlesnake Mountain, Dead Indian Creek, Crandall Creek.
Halysites gracilis (Hall). Blacksmith Fork.
Streptelasma corniculum Hall. Goose Creek Ridge, Dead Indian Creek (sp.?), Crandall Creek.
A new cyathophyllid coral. Crandall Creek.

Member 2:

Receptaculites oweni Hall. Crandall Creek.
Halysites gracilis (Hall). Dead Indian Creek, Crandall Creek.
Streptelasma corniculum Hall. Crandall Creek.
Zygospira sp. Crandall Creek.
Clinoceras(?) sp. Crandall Creek.

Member 1, within 5 feet of top (Goose Creek only):

Lophospira sp.
Raphistoma(?) sp.
Cyrtoceras(?) sp.
Orthoceras sp.
Receptaculites oweni Hall.

EARLY ORDOVICIAN (BEEKMANTOWN) (BLACKSMITH FORK ONLY)

Member 4, near top:

A small *Streptelasma*-like coral.
A small cylindrical bryozoan.
Several species of orthid and strophomenoid brachiopods, including a form probably identical with that called by Walcott[1] "*Orthis testudinaria*," from the Upper Pogonip; a form very similar to, and perhaps identical with, the one called by White[2] "*Strophomena fontinalis*"; and a form which is probably identical with that called by Walcott[3] "*Orthis perveta*."
Two species of low-spired gastropods.
Orthoceras sp. (small, annulated form).

[1] C. D. Walcott, "Paleontology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs*, VIII (1884).

[2] C. A. White, "Invertebrate Paleontology: Report upon Geographical and Geological Surveys West of the One Hundredth Meridian," IV, Part 1 (1875), Engineer Department, United States Army.

[3] *Op. cit.*

Cf. *Bathyurus*? (*Hystricurus*?) *tuberculatus* Walcott.
Ceraurus(?) sp.
An *Isotelus*-like pygidium.

Member 4, 390 feet above base:
Lingula, 2 sp.
Two species of strophomenoid brachiopods; the same as the first two of the three forms mentioned in the fauna collected near the top of Member 4.
Orthoceras sp. (small, annulated form).
Asaphus(?) sp.
Ceraurus(?) sp.

UPPER CAMBRIAN

Member 3.
Billingsella coloradoensis(?) (Shumard). Antler Peak.
Eoorthis cf. *remnicha* Winchell. Teton River.
Obolella(?) sp. Teton River.
Agnostus sp. Teton River.
Ptychoparia(?) sp. Antler Peak, Teton River(?).
Trilobite fragments. Blacksmith Fork.

Member 2:
Unidentifiable organic (algal?) structures. Blacksmith Fork.

Member 1:
Spheroidal algae, $\frac{1}{4}$ inch to 2 inches in diameter. Blacksmith Fork.

Member 0, top (Blacksmith Fork only):
Billingsella coloradoensis (Shumard).
Lingulella manticula (White).
Agnostus.
Ptychoparia.

DISCONFORMITIES

In the following statement is listed the evidence pointing toward discontinuity of sedimentation at the several horizons indicated.

8. Between Members 20 and 21 of the Devonian system (between Devonian and Mississippian?):

a) Member 20B, a limestone, 361 feet thick at Blacksmith Fork, has no lithologically similar representative in any of the other sections, unless it be a 10-foot limestone at Logan, Montana.

b) Member 21 rests on Member 19 at Crandall Creek and at Dead Indian Creek.

c) At Labarge Mountain, Teton River, and Livingston Peak, according to the writer's interpretation, the Madison limestone rests directly on Member 19.

d) Where Members 20B and 21 are absent, the thickness of Member 19 is variable, though not extraordinarily so.

e) Member 21 consists of clastic sediment, chiefly sandstone and black or deeply stained shale.

f) Member 21 contains "a fauna which is different in most of its forms from that of the lower members, and is more like that of the Madison limestone"[1] which overlies it.

7. Between Members 18 and 19 of the Devonian system (between the Jefferson limestone and the Three Forks formation):

a, Sharp lithologic change at this horizon.

b, Member 18 is moderately variable in thickness.

c, In the Teton River section the base of Member 19 contains nodules of limonite. In the Crandall Creek section the same horizon is very deeply iron-stained and carries small geodes of amorphous hematite.

It will be noted that this evidence is entirely circumstantial.

6. Between Members 14 and 15 of the Devonian system (between the main and upper divisions of the Jefferson dolomite):

a) There is a 16-foot sandstone at this horizon in the Labarge Mountain section, and much sandstone in Member 15 in the Teton River section.

b) Members 11–14, with a maximum aggregate thickness of 550 feet, are absent in the Teton River, Antler Peak, and Crandall Creek sections.

c) Members 12–14 are not known north of Labarge Mountain.

d) The Nevada limestone of eastern Nevada includes a lower and an upper fossiliferous zone, separated by from 2,000 to 4,000 feet of barren beds. The Jefferson fauna includes elements of both of the fossiliferous zones of the Nevada, suggesting that the great thickness of the Nevada is due to the presence of medial barren members which are not found in the Jefferson.[2]

e) In the Snowy Mountain section in Yellowstone Park, Weed[3] describes a 25-foot belt of limestone conglomerate at what may be this horizon.

5. Between Members 3 and 4 of the Devonian system (between the basal and main divisions of the Jefferson dolomite):

a) There is a 10-foot bed of sandstone (Member 4) at this horizon in the Labarge Mountain section, and a thinner bed of extremely sandy dolomite in

[1] W. P. Haynes, "The Fauna of the Upper Devonian of Montana, Part 2, The Stratigraphy and the Brachiopoda," *Annals of the Carnegie Museum*, X (1916), 27. It is to be noted that Haynes reached the conclusion that, nevertheless, "there is no sharp break in the record here" (*ibid.*, p. 20).

[2] See discussion of "The Jefferson Dolomite."

[3] W. H. Weed, "Geology of the Southern End of the Snowy Range," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. vi, p. 206.

the Teton River and Crandall Creek sections marks the base of the main division of the Jefferson.

b) Member 3 was not recognized in the Antler Peak or Dead Indian Creek sections, and in no known section north of Labarge Mountain does it have more than a small fraction of its thickness in that locality.

c) No part of the basal division of the Jefferson was recognized in the Logan section.

4. At the base of the Devonian system:

a) The Silurian system, 750 or more feet thick in northern Utah, is not known in Wyoming or in Montana.

b) The Upper Bighorn dolomite, which underlies the Devonian in western Wyoming and in part of southern Montana, varies greatly in thickness in that region.

c) Members 8 and 9 of the Ordovician system, which elsewhere attain a net thickness of 270 feet, are not found in the Teton River section.

d) In Montana, west of the Gallatin Range, the Devonian system rests on Cambrian strata.

To summarize points (*a*) to (*d*), the Devonian system in different parts of the central Rocky Mountain region rests upon the Silurian, the Ordovician, and the Cambrian, respectively.

e) In the Teton River section an erosion surface marks the base of the Darby formation.[1]

f) In the Crandall Creek section there is at this horizon a thin conglomerate of small rounded pebbles of dolomite in a matrix of laminated, iron-stained shale, overlain by thin lenses of very deeply iron-stained shale. The basal bed varies notably in thickness within a few yards along the strike, showing that it was deposited upon an irregular surface.

It is obvious that there is a hiatus at the base of the Devonian system wherever the Silurian is missing.

3. At the base of the Silurian system:

a) In the Blacksmith Fork section there is an indubitable erosional disconformity at this horizon.

b) The brachiopod fauna above this disconformity is wholly different from any found below it.

2. Between Members 5 and 6 of the Ordovician system (between the Trenton series and the Richmond series, Lower and Upper Bighorn, Lower and Upper Fish Haven, Lower Bighorn and Leigh):

a) In the Crandall Creek, Dead Indian Creek, and Teton River sections there is a well-marked erosional unconformity at this horizon. (Also at the

[1] Eliot Blackwelder, personal note.

base of the Fish Haven dolomite in the Randolph quadrangle, Utah; but this may perhaps be at the base of the Trenton.)

b) In the Crandall Creek, Dead Indian Creek, and Teton River sections there is at the base of the Upper Bighorn (or Leigh) a breccia or conglomerate of dolomite pebbles in dolomitic or shaly matrix, up to several feet thick; and similar conglomerate occurs at the base of the Upper Fish Haven in the Blacksmith Fork section.

c) Thin lenticular bands of deeply stained shale appear in and above the conglomerate in the Dead Indian Creek section, and the matrix of the conglomerate is deeply iron-stained both there and in the Teton River section.

d) Member 5 is not known south or southwest of Cody, Wyoming.

e) A hiatus between Trenton and Richmond was inferred by Darton[1] in the Bighorn Range from paleontological evidence.

1. At the base of the Middle Ordovician series (Lower Bighorn, Lower Fish Haven):

a) Throughout Wyoming, Montana, and South Dakota, wherever the Bighorn formation (or a formation correlated with it) exists it rests upon strata which are classed as Cambrian, and which certainly in no case are younger than Beekmantown.

b) The basal member of the Bighorn at several localities in Wyoming is a sandstone, of variable thickness, suggesting deposition on an uneven surface.[2]

c) In the Dead Indian Creek section the base of the Bighorn is a slightly irregular surface.

d) In the Randolph quadrangle the Fish Haven dolomite (all of Richmond age[?]) rests disconformably on the Swan Peak quartzite.

e) The Swan Peak quartzite is entirely missing from the Blacksmith Fork section, although it is several hundred feet thick a few miles northeast and a few miles southwest of that locality.

f) In eastern Nevada the contact between the Lone Mountain limestone and the Eureka quartzite is clearly an erosion surface.

[1] N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.* (Folio 141, 1906), p. 4.

[2] Cf. N. H. Darton, "A Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 547.

[*To be continued*]

SOME FACTORS AFFECTING THE DEVELOPMENT OF MUD-CRACKS[1]

E. M. KINDLE
Geological Survey of Canada, Ottawa

INTRODUCTION

Casual examination of the apparently erratic lines known variously as mud-cracks, sun-cracks, and shrinkage-cracks affords little promise of results of interest from their systematic study. The great geologic interest which these products of desiccation possess in connection with the history of formations in which they occur should nevertheless encourage the geologist to ascertain what effect variation in the conditions under which they are formed will have on the resulting kind or type of mud-crack. With the object of ascertaining the nature and extent of the modification of the type of mud-crack which may result from varying the conditions of its formation, I have carried out the laboratory experiments described below. These have been planned with a view to discovering (*a*) the relative effects of rapid and slow desiccation on the same mixture, (*b*) what influence, if any, composition of the mud has upon the mud-cracks, (*c*) the possibility of producing parallel mud-cracks, and (*d*) the differences which distinguish saline from fresh-water mud-cracks.

EXPERIMENTS

Two kinds of clay have been used. In experiments 1 and 3 a mud was used which came from the bottom of Lake Ontario, at a depth of 630 feet, and represented very fine-textured material. The other experiments were made with blue marine clay of Pleistocene age from the Ottawa valley near Ottawa. This is also a very fine-textured and tenacious clay.

Experiment 1.—Lake clay which was thoroughly mixed with about 5 times its volume of fresh water was poured into two

[1] Published with the permission of the Director of the Geological Survey of Canada.

porcelain vessels of the same shape and size, each being completely filled. One of these was set in direct sunlight when the daily noon temperature exceeded 100°, and the other was kept in the shade until the water had evaporated and mud-cracks had developed. The specimen exposed to sunlight developed mud-cracks on the third day. The other vessel showed the first mud-cracks on the eighth day. When completely dried, the mud in the two vessels showed a very marked difference in the size and number of polygons outlined by the mud-cracks developed. The sun-dried mud had cracked into 6 irregular-sided polygons, while the same volume of mud, which had been slowly dried in the shade during a period about three times that given the direct sunlight specimen, showed 26 polygons. Rapid drying thus seems to produce comparatively widely spaced mud-cracks, while slow desiccation gives closely spaced mud-cracks. Some interesting incidental observations were made in connection with this experiment on the tendency displayed by the very fine sand grains to segregate themselves from the mass of the mud and to gather along the edges of the joints and the margin of the vessels holding the mixtures. This segregation of the sand grains resulted in a ring of sand around the outer margin of the mud where it came in contact with the sides of the vessel. Along the sides of many of the mud-cracks the upper angle of the polygon was edged by a continuous border of sand. On the lower side of the polygon edges the sand showed no tendency to segregate. This segregation of the sand along the edges of the mud-cracks appeared to be dependent in part upon the extreme fineness of the grains. An attempt to repeat this phase of the experiment by adding sand of average fineness to mud which was desiccated in the sun failed to show any segregation phenomena, presumably because of the larger size of the sand grains used.

Experiment 2.—This experiment was designed to show what effect variation in the composition of the mud used would have on the character of the mud-cracks. Three parallel experiments were carried out for this purpose. The fine-textured blue clay of Pleistocene age from the Ottawa Valley was used. A mixture of this clay with 3 quarts of water was divided into three equal parts. To one of these (3*a*) was added 2 ounces of fine sand. The same

amount of powdered marl was added to the second (2*b*), while the third lot was left a clay and water mixture (2*c*). These three mixtures, representing sandy mud, marly mud, and clay mud, were placed in three shallow pans for desiccation in the sun. The resulting mud-cracks show that the clay mud (2*c*) cracked into much larger polygons (Fig. 1) than either the sandy or marly mud (Fig. 2). The sandy mud (3*a*) developed more than three times as many

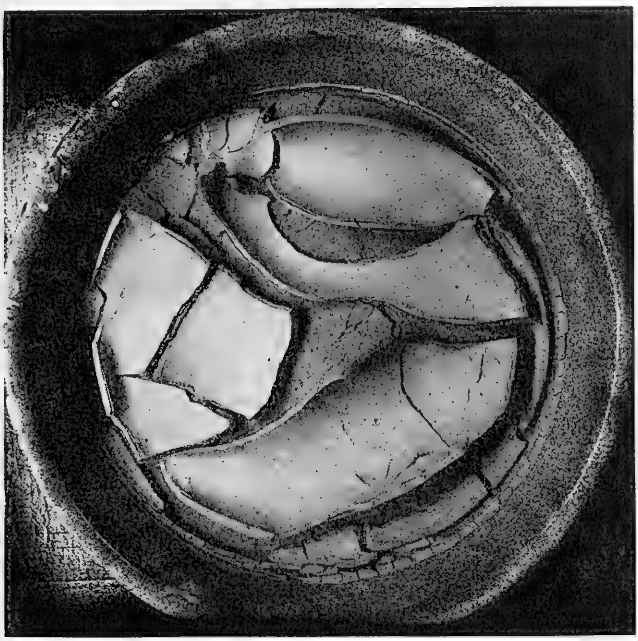

FIG. 1.—Normal fresh-water mud-cracks in blue-clay mud. ¼ natural size

polygons (Fig. 3) as the clay mud, while the marly mud showed more than twice as many polygons as the clay mixture. The large number and very angular course of many of the mud-cracks in the sandy mixture are characteristic features which distinguish this mixture from either of the other two.

Experiment 3.—A portion of the same clay mixture used in experiment 1 was placed in a shallow pan 11 inches in diameter. The water was allowed to evaporate slowly without exposure to

the sun. One side of the pan was raised $\frac{1}{10}$ inch higher than the opposite side, so that near the end of evaporation the lower side remained moist after the upper side had become quite dry, the object being to see what effect, if any, this drying out of the mud in a lateral direction would have on the character of the mud-cracks. The result of this experiment is shown in the photograph (Fig. 4), which was made before the lower margin had entirely dried, the moist portion being indicated by the darker part near the base of the picture. Instead of the usual reticulated mud-crack lines, most of the mud split up into a set of ribbon-like strips averaging $\frac{1}{2}$ inch in width and having a length of 3 to 6 inches. The direction of the mud-cracks which gave this ribbon-like effect was transverse to, and evidently controlled by, the zone separating the completely dried from the

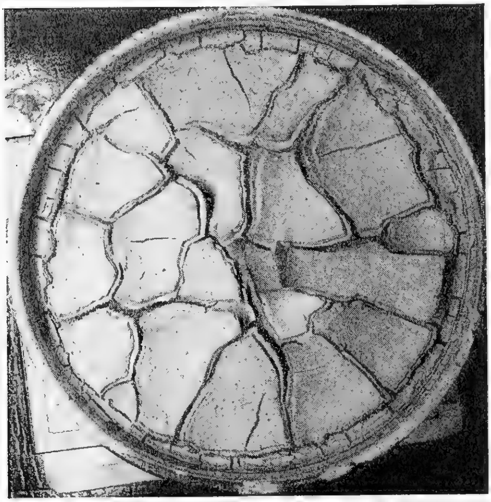

FIG. 2.—Mud-cracks in mud composed of clay and marl. $\frac{1}{4}$ natural size.

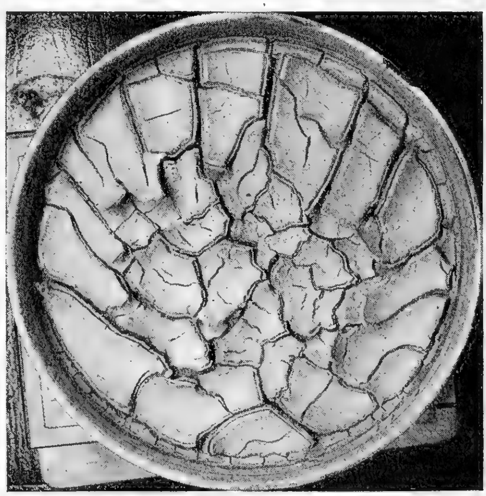

FIG. 3.—Mud-cracks in sandy mud. $\frac{1}{4}$ natural size.

partially dried mud (see Fig. 4). The cracks developed with the retreat of this zone away from the area which first dried. In a small patch of this first dried section no mud-cracks formed. This experiment shows that approximately parallel mud-cracks may be developed by differential desiccation, and affords a clue to the cause of certain kinds of joints which appear to be definable as parallel mud-cracks of considerable vertical extent.

FIG. 4.—Mud-cracks cutting the mud into ribbon-like strips. $\frac{1}{4}$ natural size

Experiment 4.—A 2-quart mixture of blue clay and water was divided into two equal parts. A tablespoonful of salt was added to one of these, and the other was left fresh. The two mixtures were placed in shallow pans $9\frac{1}{2}$ inches in diameter and put in the sun for evaporation and desiccation. Complete drying or desiccation of the salt-water pan was finished on the eighth day after starting this experiment. The first noted difference between the two pans was the earlier drying out of the saline mixture. All the liquid water had left the salt-water mixture at least a day before the fresh-water mud had ceased to be a semi-liquid mass. The desiccation was finished in a temperature of 110°.

In the fresh-water mixture preliminary mud-cracks developed on a dried-surface layer of the thickness of paper two days before the mixture underneath had lost its semi-liquid character. The earlier drying out of this surface layer of paper-like thinness retarded the drying of the lower layers and led to the excessive curling of the polygons as they were cut out by the developing mud-cracks. A lot of closely curled pieces of sediment resembling shavings repre-

FIG. 5.—Desiccated fresh-water mud. $\frac{1}{4}$ natural size

sented the final stage of the mud-crack development in the fresh-water mixture (see Fig. 5). An interesting feature of this experiment is the difference in color exhibited by the thin uppermost layer, which had been directly exposed to the air and sun, and the sediment below. The topmost film had a lead-gray color, while the sediment below it showed a creamy-white color in no way resembling the original blue clay. The general character of the mud-cracks shown by this pan corresponds closely to those most commonly met with in nature except in the extreme curling of the polygons.

The behavior of the saline mixture was markedly different from that of the fresh-water one. Except for a crack extending round

the margin of the pan and separating the mud adhering to the side from that on the bottom no regular mud-cracks developed until a very late stage of the desiccation. Instead of the usual familiar, somewhat erratic, mud-crack lines seen on drying mud, a five-rayed star-shaped figure (see upper right-hand quarter of Fig. 6) cutting to the bottom of the sediment first appeared. A day later two other figures developed, each having three lines of equal length and form-

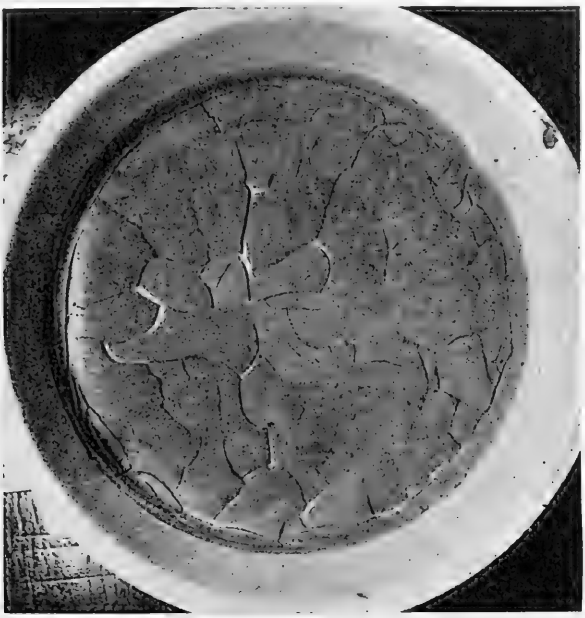

FIG. 6.—Desiccated saline mud. The same quantity and kind of mud was used as in Fig. 5 except that salt was added. Note that margins of polygons are curved downward instead of upward as in the fresh-water mud-cracks shown in Figs. 1, 2, 3, and 5. $\frac{1}{4}$ natural size.

ing at their junction angles of 120°. Simultaneously with the development of the three-line figures the entire surface became marked by small hexagonal polygons with a diameter ranging from $\frac{1}{8}$ inch to $\frac{1}{16}$ inch and giving it a honeycomb appearance. These may be seen indistinctly on the left half of Fig. 6. These were not sharply defined nor marked off by mud-crack fissures, but were discernible through a slightly lighter color of the sediment along the bounding lines, and in some cases by a slight deliquescence of

salt along these lines. These small polygons appear to represent the convection cells of Benard,[1] Dauzére,[2] and Sosman,[3] and have no direct relationship to mud-cracks. A few hours after the appearance of the triradiate figures some regular mud-cracks formed in the median portion of the pan, cutting a limited area into rather small polygons. Two of these mud-cracks were extensions of arms of the three-line figures previously mentioned. Two days after the desiccation appeared to have been completed, the remainder of the surface cracked, after being removed from the sun, splitting the entire surface into polygons. A noteworthy feature of these polygons is downwarping of their margins and absence of lateral shrinkage, which is in sharp contrast with the upwarping of the sides and considerable shrinkage of polygons which formed from the fresh-water mud. In fact, the saline mud showed as a whole slight lateral expansion which was taken up by the arching upward of the median portions of the polygons.

Considered from the standpoint of preservation as permanent features in the strata of consolidated rocks, mud-cracks in saline clays would have a rather poor chance of permanent preservation owing to their slight breadth. If preserved, they would be quite inconspicuous as compared with ordinary mud-cracks. The star-shaped figures, however, by reason of their broad and deeply incised arms lend themselves well to preservation under natural conditions of sedimentation and should be regarded, when found on rock surfaces, as evidence of subaërial desiccation. This experiment represents the behavior of highly saline mud such as would be found on the shores of salt lakes or detached arms of the sea rather than that of the muds ordinarily met with about the estuaries of rivers, which have a much lower degree of salinity.

The salinity of ordinary estuarine mud was approximated in another experiment. Sea water was used in still another. In all these supplementary experiments, including a sample of mud having less than the salinity of ordinary tide-flat mud, desiccation produced

[1] H. Benard, *Les Tourbillons cellulaires dans une nappe liquide*, etc., thesis, Paris, 1901; *Rev. gen. Sci.*, XI (1900), 1261–71, 1309–38.

[2] C. Dauzére, *Jour. physique*, VI (1907), 892–99; VII (1908), 930–34; *Assn. franc. av. sci.*, 1908, pp. 289–96.

[3] Robert B. Sosman, "Types of Prismatic Structure in Igneous Rocks," *Jour. Geol.*, XXIV (1916), 219–24.

polygons in which the upper and lower surfaces were perfectly flat, the edges showing no inclination either to warp up or down.

SUMMARY AND DISCUSSION

The experiments described above justify the following deductions: Rapid desiccation produces mud-cracks which are more widely spaced than those produced by slow desiccation. In mud-cracks occurring in rocks of the same or similar composition the relative size of the resulting polygons would therefore serve as a basis for inferring the relative temperatures under which they were formed.

The composition and the resulting tenacity of the mud very materially affects the spacing of the mud-cracks. The presence of marly material or the addition of sand gives polygons which are much smaller than those formed in clay mud (Figs. 1–3). In the case of sandy mud a sufficient excess of sand entirely prevents the formation of mud-cracks. Hence a bed of sand might be exposed to subaërial conditions without furnishing mud-crack evidence of the fact. Temperature and tenacity of the material are two primary factors in controlling the spacing of mud-cracks.

Approximate parallelism of mud-cracks may result from zonal drying of the mud. The parallelism seen in many systems of joint structure may thus be duplicated under special conditions in shrinkage-cracks in mud.

A high degree of salinity delays the formation of mud-cracks and results in polygons in which the margins are inclined downward (Fig. 6). These are in marked contrast to the polygons formed in fresh-water mud, which dish upward, saucer-like (Figs. 1, 2, 3, and 5). The polygons formed in mud with the salinity of ordinary sea water warp neither upward nor downward at the margins, but retain a flat surface. It should be pointed out here that the marked differences observed in the experiments between the behavior of fresh-water, highly saline, and moderately saline muds are not ordinarily so well marked in nature as the accompanying illustrations might lead the reader to expect. The strong tendency, as shown by the pan experiments, of fresh-water mud to warp upward and of very saline mud to warp downward at the margins of the polygons on cracking is modified and often neutralized by

the tenacity of the mud, which on a mud flat may prevent the topmost cracked layers from partially splitting away from the subjacent layers, as they must do if this warping occurs. Clearly the cohesion between the layers of mud is greater than that between the smooth bottom of the pan and the mud in it. Observation of sun-cracked fresh-water mud on the bottom of evanescent ponds will show that the polygons warp upward or remain flat, according to the tenacity of the mud. Where the tenacity of the mud is slight, the saucer-shaped polygons are dominant.

In the case of fossil mud-cracks the geologist can make definite deductions regarding the salinity of the original mud only where there has been distinct upwarping or downwarping of the polygons. Where the surface is flat, as is usually the case, lack of warping is as likely to be due to the tenacity of the mud overcoming the warping influence of fresh water as to the normal influence of the salinity of sea water. Where the polygons show a definite saucer-like upwarp at the margins, however, the inference that they were formed from fresh-water mud would be inevitable. I have described[1] from bed A of the Mount Wissick section in New Brunswick an example of this kind which in the light of these experiments must be referred to continental or fresh-water conditions, although I originally supposed it to have been formed on a tidal flat.

Fossil examples of the inverted-saucer type of polygon due to the drying of very saline muds are apparently not very common. Some peculiar structures in Silurian dolomite described by Gilbert[2] and illustrated[3] by Kindle probably represent a phase of this phenomenon. These curved plates in the Lockport dolomite near Niagara Falls, which are probably the result of the desiccation of highly saline sediments, were supposed by Hall to be of concretionary origin. They immediately precede in the section a rock series in which beds of gypsum and rock salt afford conclusive evidence of the highly saline character of the sediments deposited a little later.

[1] *Geol. Surv., Can. Mus. Bull. 2*, 1914, p. 37.

[2] "Undulations of Certain Layers of the Lockport Limestone" (Abstract), *Science*, N.S., XXI (1905), 224.

[3] *U.S. Geol. Surv. Folio No. 190*, 1914, p. 59, Pl. 24.

DOWNWARPING ALONG JOINT PLANES AT THE CLOSE OF THE NIAGARAN AND ACADIAN[1]

LANCASTER D. BURLING
Canadian Geological Survey, Ottawa

The upper part of the Lockport dolomite exhibits a number of interesting structural features. These are not confined to the Lockport, but many of them have an important bearing on the physical conditions during and immediately succeeding the formation of the Lockport and as such deserve attention. Among the most striking of these are: (1) the huge vase-like residual masses of the Lockport on Flowerpot Island[2] in the Bruce Peninsula of Ontario; (2) the widespread doming of the strata which Kindle has described[3] as probably analogous in origin to the mud lumps at the mouth of the Mississippi; (3) the arching of the strata forming the uppermost or Eramosa beds of the Lockport dolomite in Ontario, where it is ascribed in at least one instance[4] to the presence of an underlying coral reef; (4) the burial of Devonian rock and fossils in joints 18 feet below the present glaciated surface of the Niagara limestone in Illinois;[5] (5) the anticlinal arches which characterize the Lockport in the Niagara region, and which Kindle and Taylor[6] ascribe to local stresses of comparatively recent date; (6) the ripple-mark and other sedimentation phenomena which have been described so frequently;[7] (7) the immediate superposition above the Lockport of the Salina with its salt and gypsum;[8]

[1] Published by permission of the Deputy Minister of Mines.

[2] Stauffer, *Geol. Surv. of Canada, Guide Book No. 5*, 1913, p. 75.

[3] *Amer. Jour. Sci.*, 4th Ser., XV (1903), 459–68.

[4] Williams, *Geol. Surv. of Canada, Museum Bull. No. 20*, 1915, pp. 1–2. It should be noted, however, that the horizon of the Eramosa beds is below the top of the Lockport as used, for example, by Kindle and Taylor in the Niagara Folio.

[5] Weller, *Jour. Geol.*, VII (1899), 483–88.

[6] *Geol. Atlas of the U.S., U.S. Geol. Survey*, Niagara Folio (No. 190), 1913, p. 109.

[7] Cf. Kindle, *Geol. Mag.*, Dec. 6, I (1914), 158–61.

[8] Cf. Grabau, *Bull. Min. and Metal Soc. Amer.*, VI, No. 2 (1913), 33–44.

and (8) the local downwarping along joint planes, to which this paper is directed.

The downwarping of certain layers near the top of the Lockport dolomite has been the subject of frequent reference, and illustrations of it have been copied and recopied. The structure was first described by Hall, who characterized it as concretionary.[1] Chamberlin and Salisbury[2] first called attention to the fact that the sag is along joint planes, an explanation which is concurred in by Hobbs,[3] but neither of these authors makes any comment regarding the period of deformation. This was first treated by Gilbert in 1905 in a paper of which we have only an abstract. After describing the structures he says[4] that he is not satisfied with Hall's characterization of them as concretionary, but that they were probably contemporaneous with the deposition of the strata and not subsequent to it.

The phenomenon has been described for the following localities: (1) Niagara limestone at Porter's quarry, Niagara Falls;[5] (2) Niagara limestone, Cook's quarry, near Lasalle, Niagara County, New York;[6] (3) Lockport dolomite, Niagara Falls: (*a*) in new railroad cutting; (*b*) in quarry 3 miles east of the city; and (*c*) in water channels temporarily exposed at the Dufferin Islands on the Canadian side;[7] (4) Lockport dolomite, Niagara Falls, old quarry 1½ miles east.[8]

The purpose of this paper is to show that such structures are essentially contemporaneous with the deposition of the strata, that they should be expected to occur where they do, that they are important, and that they have formed under essentially similar

[1] *Geol. New York*, Part 4 (1843), p. 94, Fig. 30.

[2] *Geology* (New York: Henry Holt & Co., 1904), I, 150, 151.

[3] *Earth Features and Their Meaning* (New York: Macmillan, 1912), p. 224, legend to Fig. 239.

[4] *Science*, N.S., XXI (1905), 224.

[5] *Geol. New York*, Part 4 (1843), p. 94, Fig. 30.

[6] Chamberlin and Salisbury, *Geology* (New York: Henry Holt & Co., 1904), I, Fig. 137, p. 151.

[7] Gilbert, *Science*, N.S., XXI (1905), 224.

[8] Kindle and Taylor, *Geol. Atlas of the U.S.*, *U.S. Geol. Survey*, Niagara Folio (No. 190), 1913, Illus., III, Pl. XXIV.

conditions in rocks of Cambrian age where the evidence as to their early origin is conclusive.

In all of the Lockport localities that have been described the warped surface directly underlies till or marine clays. During the field season of 1915 a similar warped surface was discovered to be characteristic of the uppermost beds of the Middle Cambrian in British Columbia. These are dolomites and form the top of the Eldon formation. The basal beds of the Upper Cambrian rest directly upon this warped surface and, as if to yield further confirmation of the fact that the beds forming the top of the Eldon suffered prolonged exposure to the air and that such a condition continued during the period of deposition of the basal beds of the overlying Bosworth formation, the latter is full of mud-cracks, ripple-marks, and casts of salt crystals 2 inches or more in diameter.

The phenomenon was studied in the amphitheater north of Castle Mountain, and there is here no question that the warping was essentially contemporaneous with the deposition of the strata. It is interesting to note that the only known occurrences of this peculiar type of warped structure in both cases occur at the top of a dolomite overlain by shales with salt crystals and evidences of salinity. In the Lockport, Grabau[1] is of the opinion that the overlying Vernon suggests the accumulation of fine loess-like material, chiefly as wind-blown dust. This is of interest in connection with the theory of the eolian origin of the salt deposits of India discussed by Holland and Christie.[2] The bed immediately overlying the warped structure at the top of the Eldon is almost a pure dolomite, and the warped layers whose depressions it fills contain almost as little calcium carbonate. Grabau[3] describes the section between the Lockport and the Salina as composed of a "stratum of thin-layered bituminous accretionary limestone, forming flat, imbricating, shell-like domes" overlain by 2 feet of yellow impure limestone, which is in turn succeeded by the green shale forming the base of the Salina. In this paper on the early Paleozoic Delta deposits of North America, Grabau goes into the physical conditions

[1] *Bull. Geol. Soc. Amer.*, XXIV (1913), 490.

[2] *Rec. Geol. Survey India*, XXXVIII, Part 2 (1909), 154–86.

[3] *Bull. Geol. Soc. Amer.*, XXIV (1913), 491.

of Niagara time in great detail, but does not mention the warped surfaces. Likewise Clarke and Ruedemann, in their memoir on the Guelph,[1] do not mention these structures in their discussion of the conditions of life and sedimentation during the prevalence of this fauna. Writers agree, however, that there was a shallowing of the sea near the close of Lockport sedimentation and a gradual increase in its salinity and the magnesian content of its waters. Arguing from the extraordinary thickness of the Guelph molluscan shells, Kindle and Taylor[2] postulate the subjection of the bottom of the Silurian sea at this time to intense wave-action. Calvin[3] accepts the theory which had already been suggested by Hall that "at the close of the Niagara huge mounds and ridges were built on the bottom of the shallow Silurian sea, in part by the accumulation *in situ* of corals, crinoids, and molluscous shells, and in part by the drift of calcareous sediments under strong currents."

I am inclined to the opinion, and this appears to be corroborated by the position and physical character of the sediments involved, that the sagging of these beds, both those in the Eldon of British Columbia and those in the Lockport of New York, was largely caused by the gentle scour of water at a time soon after deposition. In each case the horizon of the warped structures is the locus of pronounced changes in the paleontologic record. In the Lockport the time was one of a prolonged emergence and marked the close of the Niagaran; in the Eldon it marks the close of the Middle Cambrian or Acadian and doubtless indicates a similar period of emergence at that time. Walcott, who did not, however, have the advantage of having seen the salt crystals of the Bosworth formation, says: "It is difficult to resist the conclusion that the 268 feet of shales forming the base of the Bosworth Upper Cambrian section were deposited in fresh or brackish water or on a river flood plain or delta such as Barrell describes so graphically in his studies of the *Geological Importance of Sedimentation*."[4] The warped structure at the top of the Middle Cambrian in British Columbia has been

[1] *New York State Museum, Mem. No. 5* (1903), 114–21.

[2] *Geol. Atlas of the U.S., U.S. Geol. Survey*, Niagara Folio (No. 190), 1914, p. 116.

[3] *Geol. Survey Iowa, Rept.*, 1896, p. 129.

[4] *Problems of American Geology* (Yale, 1915), p. 185.

observed, not only in the Castle Mountain section along the Canadian Pacific Railway, but in the Mount Robson section of the Grand Trunk Pacific 200 miles to the northwest. In each case it is followed by reddish-purple, green, and yellow shales, with ripple-marks, mud-cracks, and casts of salt crystals.

Salt crystals, previously known only from pre-Cambrian and post-Ordovician rocks, have been assumed, and rightly, to indicate arid conditions and more or less emergence. The peculiar type of downwarping described appears to be the natural result of the quiet subaërial exposure of recently consolidated dolomitic limestones under conditions of aridity. Whether or not the downwarping described is necessarily contemporaneous with aridity, it is certainly a feature due to subaërial exposure, and the probabilities are in favor of its formation at the time of the deposition of the strata rather than subsequently. This necessarily involves the assumption that the joints along whose channels the solution was localized came into existence very soon after the deposition of the strata and were relatively contemporaneous with the deposition of the beds. The evidence as to the early origin of the warped structures is so conclusive that we are justified in disregarding such coincidences as the immediate superposition, where so far discovered, of tills and clays upon the warped Lockport and such inferences as that, since the solution took place along joint planes, it must be comparatively recent. Have we not here rather a slight measure of the duration of the time-break in the deposition between the Middle and Upper Cambrian, and between the Niagaran and the Cayugan, and are we not justified in bearing in mind the principle of relatively contemporaneous consolidation and jointing in rocks?

THE WESTERN INTERIOR GEOSYNCLINE AND ITS BEARING ON THE ORIGIN AND DISTRIBUTION OF THE COAL MEASURES[1]

FRANCIS M. VAN TUYL
University of Illinois

While occupied with a study of the stratigraphy of the Mississippian formations of Iowa for the Iowa Geological Survey the writer has been attracted by the regular and nearly uniform gentle dip of these formations to the southwestward, and he has recently attempted to ascertain the age and significance of the deformation which gave rise to this. Investigation soon showed that the tilting was related to deformation over a wide area in southern Iowa, southeastern Nebraska, eastern Kansas, and northwestern Missouri which outlined a great southwestwardly pitching geosyncline in which the Coal Measures of the western interior coal field were deposited. The evidence is clearly in favor of the view that the movement took place, in part at least, during pre-Pennsylvanian time, as shown by the fact that the Coal Measures now rest upon trunkated Mississippian formations successively younger in age toward the southwest. This belted arrangement of the Mississippian deposits beneath the Coal Measures cannot be accounted for on the assumption that the distribution of the former is original, since the beds often consist entirely of nearly pure limestone up to their very boundaries and show no indications of shore facies.

That the geosyncline was shallow in early Pennsylvanian time is indicated by the fact that the maximum known thickness of the deposits of the Cherokee stage, which probably represents the time of greatest sea extension in this basin during the Pennsylvanian, is only 712 feet. At the present time, however, it attains a known depth of approximately 2,400 feet at McFarland, Kansas, and future drill records will probably show it to be considerably deeper than this to the southwest. The deepening is believed to have

[1] Published with the permission of the Director of the Iowa Geological Survey.

been brought about in part by subsidence during the post-Cherokee stages of the Pennsylvanian and in part by post-Pennsylvanian deformation. The data are not sufficient at present to warrant an estimate of the relative importance of each of the two. There is evidence that the original outlines and relations of the basin have been considerably modified by these later readjustments.

The magnitude and significance of the basin have been demonstrated by the construction of 100-foot contours on the base of the Coal Measures, from data furnished by the reports of the state geological surveys of Iowa, Missouri, and Kansas (Fig. 1). Contours showing the altitude of the base of the Coal Measures in Missouri have already been drawn by Hinds and Greene,[1] and these have been copied directly. Norton has also drawn a similar contour map for the southwestern and south-central portions of Iowa,[2] and this has been adopted with little modification.

The presence of this basin not only explains the great dissimilarity between the Coal Measures of this field and those of the eastern interior field, which were undoubtedly deposited in a distinct basin, but also explains the belted arrangement of the outcrops of the Pennsylvanian formations in Iowa, Missouri, and Kansas, where the younger members are approximately confined to the center of the basin, progressively older ones being exposed toward its margins.

There can be no doubt that this geosyncline exerted an important influence on sedimentation in this region during the Pennsylvanian. The work of Hinds and Greene in Missouri has furnished valuable data bearing on this point. Referring to the Cherokee deposits of that state they say:

> The Cherokee sea, advancing from the west or southwest, first invaded Missouri in the vicinity of Forest City, Holt County, and soon extended northeast as a long shallow arm through Worth, Harrison, and Mercer counties into Iowa. When about 150 feet of Cherokee sediments had been laid down the arm had broadened out to the southeast so as to embrace Buchanan and Platte counties, and a short time later Clay, Jackson, and Livingston counties. After the deposition of nearly 400 feet of material in the Forest City area the sea covered practically all of the western tier of counties, except Atchison, and

[1] *Mo. Bur. Geol. and Mines*, Vol. XIII, 2d Ser. (1915), Pl. 25.

[2] *Iowa Geol. Survey*, XXI (1912), 1101.

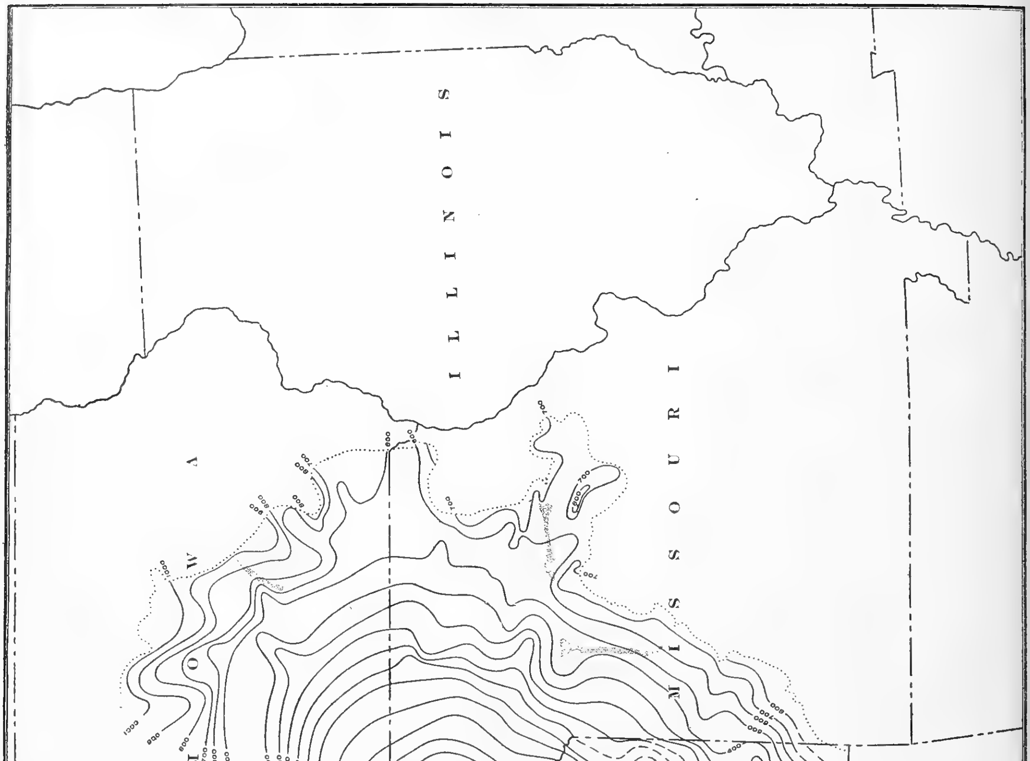
ILLINOIS
IOWA
MISSOURI
NEBRASKA
KANSAS
MAP
SHOWING
WESTERN INTERIOR GEOSYNCLINE
DRAWN BY F.M. VAN TUYL AND W.S NELSON
LEGEND
Structural contours on base of "Coal Measures"
(Dashed lines indicate doubtful position of base)
Channel deposits
Approximate boundary of "Coal Measures"
SCALE OF MILES
25 0 25 50 75 100

FIG. 1.

soon extended eastward into Henry, Johnson, Lafayette, Roy, Carroll, Linn, Putnam, and Adair. When the Bevier coal bed was formed, near the beginning of Allegheny time and after the deposition of 580 feet of material at Forest City, some sedimentation had already taken place in all the region now occupied by the main body of the Pennsylvanian and a fairly large area in which there are now only small patches remaining. The land area had been reduced to an island in southeastern Missouri, with a peninsula projecting into Pike and neighboring counties and a small part of a northern land mass in the extreme northwestern corner of the state. The western sea continued to advance eastward while an eastern sea occupying most of Illinois advanced westward. Probably by the end of Cherokee time the two seas had joined, submerging practically all of northern Missouri and possibly nearly all of southern Missouri also. No deposition appears to have taken place at this time in the extreme northwestern corner of the state, for the Nebraska City drilling shows less than 100 feet of Des Moines strata, probably of Pleasanton age.[1]

That these authors are justified in this conclusion is shown by a study of the thicknesses of the Cherokee in Missouri as listed by them.[2] Thus at Forest City in Holt County the thickness is 712 feet, while its average thickness in the counties to the eastward becomes successively less and less, viz., Livingston 450, Linn 260–310, Macon 175, Audrain 75. To the southeastward a similar relationship is shown, thus: Buchanan 530, Platte 555, Clay 460, Jackson 430, and Johnson 220–350 (see Fig. 2).

The influence of the basin upon the thickness and character of the post-Cherokee stages of the Pennsylvanian is not so obvious. The writer, after a careful study of all the available data, including deep-well and drill records from various parts of the area, has not been able to find any consistent variation in the thickness and lithologic character of the formations in tracing them from the center of the basin toward its margins. Nevertheless,the, lack of relation between these deposits and those of the Illinois field suggests that the basin persisted and that its gradual though interrupted subsidence made possible the deposition of the Pennsylvanian formations of this province. It is believed that the original relations have been masked in large part by disconformities within the Coal Measures, several of which have been recognized, and by post-Pennsylvanian erosion, which has almost entirely removed the marginal facies of all the formations younger than the Cherokee.

[1] *Op. cit.*, p. 209.

[2] *Op. cit.*, pp. 39–40.

SIGNIFICANCE OF THE CHANNEL DEPOSITS

The channel deposits in the Coal Measures of Iowa and Missouri are very interesting in this connection in that they furnish

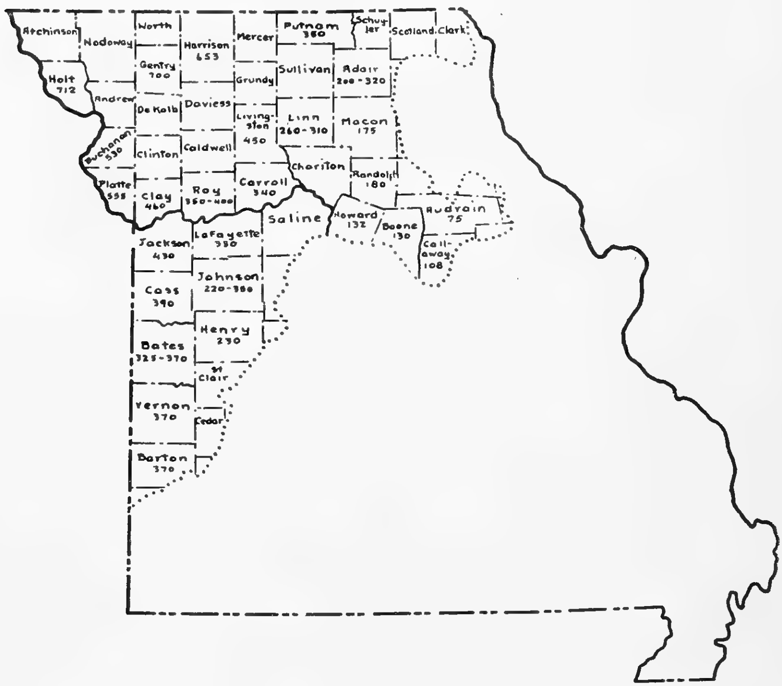

FIG. 2.—Map showing variations in thickness of Cherokee formation in Missouri. The influence of the basin is shown when this map is compared with that of Fig. 1.

corroborative evidence of the persistence of the basin in post-Cherokee time. With reference to such deposits in Missouri Hinds and Greene say:

> Among the most unique features of the Missouri Pennsylvanian are two long, narrow channels filled with sandstone and shale which have been eroded in Cherokee, Henrietta, and some Pleasanton strata in Johnson, Lafayette, Randolph, and other counties. Remnants of other channels have also been found in many parts of the Pennsylvanian area, and many more probably remain to be discovered as the net of detailed geologic work is spread over the state.
>
> The channels are of great scientific interest, for they must have been formed during an interval of more or less widespread emergence and erosion during

Pennsylvanian time. If, as suspected, the channel deposits are contemporaneous with certain sandstones and conglomerates of late Pleasanton age in north-central Missouri, this erosion interval occurred before the beginning of the Missouri epoch.[1]

The location and trend of the channels are shown on the accompanying map (see Fig. 1). The east-west channel has been designated the "Warrensburg" and the north-south one the "Moberly."

In describing these deposits Hinds and Greene state that—

the Warrensburg sandstone fills a channel about 50 miles long, extending from north of Lewis Station, Henry County, northward to the north bluffs of Missouri River. The sandstone belt, as at present exposed, has an average width of two miles, but just south of the Missouri widens to six miles. . . . .

The Moberly channel extends from South of Madison, in Monroe County, west to Chariton River south of Salisbury. Its length is nearly 40 miles and its average width less than 3 miles. The maximum depth shown in drill records is about 200 feet.[2]

With regard to the nature of the streams which gave rise to the channels the same authors express themselves as follows:

It is believed that the Warrensburg channel was made by water flowing from higher country on the Ozark dome, bringing with it sands and muds derived largely from early Pennsylvanian sediments. The Warrensburg stream was joined when it reached the present site of Missouri by the Moberly River descending westward from an Ozark peninsula in northeastern Missouri, and the united streams continued northward or northwestward to the open sea.[3]

Referring to the channel deposits presumably of a similar age in Iowa, Hinds and Greene say:

The Red Rock sandstone of Marion and Jasper counties, Iowa, lies in a channel $2\frac{1}{2}$ to 3 miles wide that has been traced for 27 miles from Eagle Rock northeastward. This sandstone has a maximum thickness of 100 feet and has all the characteristics of the Warrensburg and Moberly sandstones.[4]

It will be noted that the trend of these old channels, both in Missouri and in Iowa, indicates that the drainage development during the temporary uplift in late Des Moines time was influenced by the geosyncline.

[1] *Op. cit.*, p. 91.

[2] *Ibid.*, pp. 95 and 97.

[3] *Ibid.*, p. 93.

[4] *Ibid.*, p. 94.

POST-PENNSYLVANIAN HISTORY OF THE BASIN

Subsequent to the deposition of the Paleozoic the Mississippi Valley region was uplifted. It seems probable that the geosyncline was deepened somewhat at this time and that secondary folds were developed. But the fact that the regularity of the basin has not been appreciably interfered with indicates that this secondary folding was not of great importance. Following this uplift the region underwent peneplanation. That the deposits occupying the geosyncline were peneplained by the beginning of the Upper Cretaceous is shown by the fact that the basal deposits of this age rest upon the beveled edges of the dipping formations, ranging in age from the Lower Mississippian on the marign of the basin in Iowa to the Permian in Kansas, at approximately the same elevation everywhere.

There is no evidence of further movement of the geosyncline during or since the Cretaceous apart from the regional uplift which brought the area to its present level. The present course of the Missouri River across the basin was obviously taken some time after the development of the peneplain.

A DECIMAL GROUPING OF THE PLAGIOCLASES[1]

F. C. CALKINS
United States Geological Survey, Washington, D.C.

The accompanying diagram, which represents about half of the methods according to which the soda-lime feldspars have been grouped, reveals a surprising diversity of usage. Consistency, which undeniably would be of some advantage in the long run, is not likely to obtain until it is demonstrated that some particular scheme is better than all others. That this has not been done is perhaps because it has not been attempted; for, once the matter is given any critical attention, the most convenient and logical adaptation of current nomenclature seems rather easy to find.

The ideal plan should, first, accord with the modern doctrine that the plagioclases form a continuous series; schemes that imply a limited number of compounds (Nos. 1–3) must, therefore, be rejected.

Secondly, the intervals that separate the species in certain plans (Nos. 5, 8, 9) are needless, even when they imply no discontinuity. They then result in eleven-fold instead of sixfold division, compound names, like "andesine-labradorite," being applied to the intervals between the main species; but six terms, with qualifying adjectives, will suffice for as close discrimination as is worth while, and the awkward compound names may be reserved for feldspars that lie virtually at the junction of two species.

Finally, the division should be regular. The question arises here whether the names "albite" and "anorthite" shall be applied only to the pure soda and pure lime feldspars respectively, as in Zirkel's quite regular plan (No. 7), or whether they shall denote a certain range of composition. As absolutely pure end terms are mere abstractions, the answer to this question amounts to a choice between a fourfold and a sixfold division. It is only following universal practice to prefer the sixfold one. Now, there are but

[1] Published by permission of the Director of the United States Geological Survey.

two simple ways of dividing regularly a series of six parts: either to give all parts an equal range, or to give the end parts half the range of the others, which are mutually equal. The latter plan

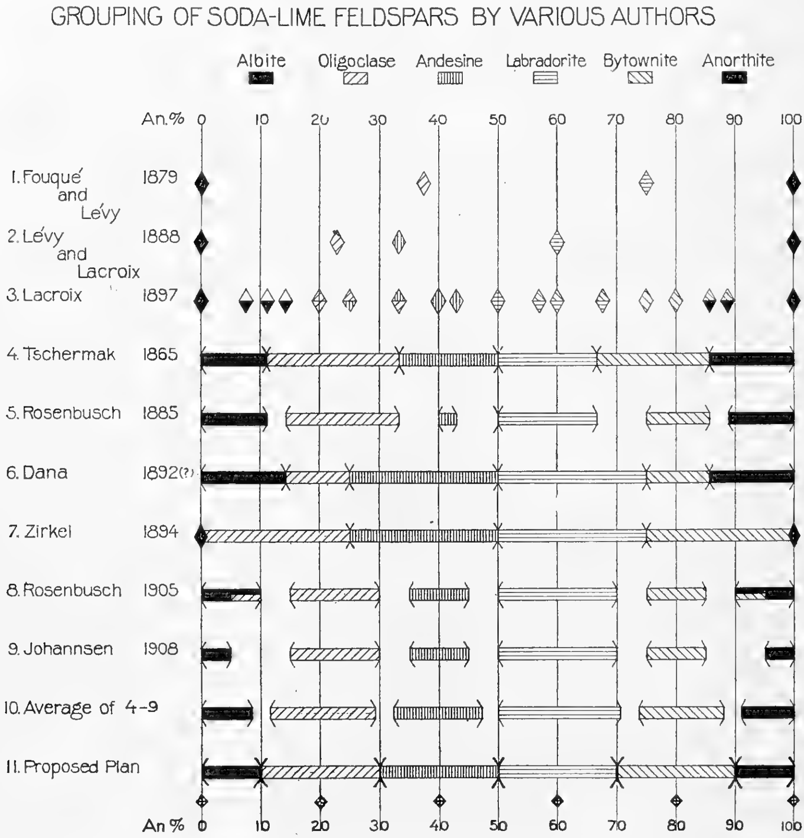

FIG. 1.—Sources of plans illustrated

1. F. Fouqué and A. Michel Lévy, *Minéralogie micrographique*, 1879.
2. A. Michel Lévy and A. Lacroix, *Les Minéraux des roches*, 1888.
3. A. Lacroix, *Minéralogie de la France et de ses colonies*, II (1897), 130.
4. G. Tschermak, "Die Feldspathgruppe," *Sitzungsberichte d. K. Akad.* Wien, L (1865), 566.
5. H. Rosenbusch, *Mikroskopische Physiographie*, etc., 2d ed., 1885 ("nach Tschermak").
6. J. D. and E. S. Dana, *System of Mineralogy*, 6th ed., 1892; also used by J. P. Iddings, *Rock Minerals*, 1906, and by F. W. Clarke, "Data of Geochemistry," *Bull. 330, U.S. Geol. Survey*, 1908.
7. F. Zirkel, *Lehrbuch der Petrographie*, 2d ed., 1894.
8. H. Rosenbusch, *Mikroskopische Physiographie*, 4th ed., 1905, Bd. I, 348.
9. A. Johannsen, *Determination of Rock-forming Minerals*, 1908.
10. Average of 4–9.
11. Decimal grouping.

seems the more logical as well as the more accordant with usage. It leaves equal spaces between the several types; for, if the most typical andesine is average andesine, the most typical albite is pure albite.

It is therefore proposed that the divisions be placed, as in Diagram 11, where the ratios of anorthite to albite are $\frac{1}{10}$, $\frac{3}{10}$, $\frac{7}{10}$, and $\frac{9}{10}$.

The questions of priority and of average practice have thus far been left in the background. If priority determined preference, Tschermak's plan (No. 4) should be preferred; and the belief seems general that his plan is most in use. But, rather oddly, the scheme that currently passes for Tschermak's is a modification thereof by Rosenbusch (No. 5). The scheme proposed in the present note resembles Tschermak's more closely than does any other. Still more closely does it resemble the scheme (No. 10) deduced by averaging the ranges of species in Diagrams 4 to 9. The slightest alteration that will regularize this "average" plan and close its gaps produces the decimal grouping.

A decimal grouping goes naturally with centesimal symbols, of which the most-used form is Ab_nAn_{100-n} (e.g., $Ab_{40}An_{60}$, or $Ab_{25}An_{75}$); these, moreover, present certain practical advantages. They give, more quickly than those like Ab_2An_3 and Ab_1An_3 a definite idea of relative composition—which is merely saying that decimals are more easily subtracted than common fractions. The decimal co-ordinates, too, upon which extinction-angle curves are plotted, indicate the composition corresponding to a given angle in percentages, which it is a needless trouble to reduce to a fraction of a small denominator. Since in such curves the anorthite increases toward the right, it is by the percentage of anorthite, rather than by that of albite, that the composition is naturally measured. Therefore, a symbol such as An 60%, or $An_{.60}$, which indicates this percentage alone, conveys the essential information more economically than the symbol $Ab_{40}An_{60}$; the former's greater convenience, however, is possibly outweighed by the greater currency of the latter.

Studies for Students

A CLASSIFICATION OF BRECCIAS

W. H. NORTON
Cornell College, Iowa

Few geologic structures so lend themselves to diverse interpretations as the beds of broken rock called breccia. Example after example might be cited of breccias of Europe and America which have been differently explained by different students during the last half-century and as to whose origin no consensus is yet attained. This diversity of opinion seems partly due to the large number of processes by which rocks are broken up, assembled, and cemented into breccia, and to the fact that breccias may offer no very obvious and indisputable evidences of the method of their making. Diagnosis generally requires the use of multiple working hypotheses and may proceed chiefly by the process of elimination. For this reason a genetic classification which the writer has prepared in connection with a field study of certain breccias affecting the Wapsipinicon stage of the Devonian of Iowa may prove of interest to students of these structures.

The diagnosis of a breccia requires the close observation of its most intimate characteristics as well as of its associations with the adjacent rocks. The matrix may be like or unlike the fragments lithologically. It may be a chemical precipitate, a sedimentary deposit, or the detritus of attrition. In volume it may be greater or less than the fragments—interstitial, merely filling the spaces between the fragments closely packed, or preponderant, forming the larger part of the rock-mass in which the fragments are sporadic.

The fragments may be of any size, from huge blocks down to chipstone. Lithologically they may be similar or dissimilar, according as they result from the fragmentation of a homogeneous rock-mass or from that of heterogeneous beds. They may be sharply angular, more or less rounded by attrition in earth movements, or even in part water-worn and approaching a conglomerate.

They may be local in derivation, produced by the breaking up *in situ* of a terrane, or they may have suffered transportation from distant sources. They may be simple or of complex and brecciated structure, the result of an earlier brecciation.

Breccia may form a mass entirely destitute of planes of bedding. When bedded in a distinct stratum it may be classified as *endostratic*.

A *crackle breccia*, representing incipient brecciation, is one whose fragments are parted by planes of fission and have suffered little or no relative displacement. The fragments match along their apposed sides. The matrix is confined to the seams and is commonly a chemical deposit.

A *mosaic breccia* is one whose fragments have been largely but not wholly disjointed and displaced. The system of continuous cracks of the crackle breccia has been destroyed, but more or less of the fragments still match along adjacent surfaces and show that they are consanguineous parts of once unbroken laminae or larger beds. The term suggested is not a happy one, yet these breccias may recall some ill-preserved mosaics of ancient ruins. The matrix is confined to the seams and to the wider and irregularly shaped interstices.

A *rubble breccia* is one in which no matching fragments are parted by initial planes of rupture. The fragments are close-set and in touch.

A *breccia of sporadic fragments* is one in which the fragments are imbedded in a preponderant matrix like plums in a pudding. It recalls the term "plum-cake rock," applied by the quarrymen of North England to the breccias of their region. In his study of the Permian Midland breccias of England, King[1] distinguishes an endostratic breccia of this class by terming it "breccia sandstone," thus emphasizing the bedded matrix rock.

Breccia may be fossiliferous. Fossils may be restricted to the fragments or to the matrix or may be found in both. Fossils of the matrix may themselves be fragments. Brecciation may be practically contemporaneous with the involved deposits. Such are the *intraformational breccias* of Walcott. In certain classes

[1] W. W. King, "Permian Conglomerates of the Lower Severn Basin," *Quar. Jour. Geol. Soc. London*, LV (1899), 105.

of breccia the matrix is of the same age as the fragments. In other classes it is younger, and in still others it may even be supplied by an older bed.

Breccia may be of slight extent and evidently due to local causes. On the other hand, some of the most perplexing breccias are regional and demand causes equally widespread in operation.

According to the conditions under which they accumulate, breccias may be classified as *subaërial*, *subaqueous*, or *endolithic*, formed within the lithosphere, the earth's crust.

In classifying breccias genetically it will be remembered that the making of a breccia involves, or may involve, three distinct processes—fragmentation, assemblage of the fragments, and cementation by the introduction of the matrix. In any given breccia all of these processes may belong to the same or to different categories. The genetic classification may have in view either fragmentation, as in crush breccias, or assemblage, as in several other types.

Subaërial breccias, in which both fragmentation and assemblage are above ground, may be classified as follows:

Residual breccia	Bajada breccia
Talus breccia	Glacial breccia
Rock-glacier breccia	Volcanic breccia
Landslide breccia	

Residual breccia.—This type is formed of the angular débris of the waste mantle. It has been designated as "basal breccia,"[1] since it corresponds in position to a basal conglomerate. But all subaërial breccias covered and preserved by the deposits of a transgressing sea may correspond equally well to basal conglomerates, so that some designation seems preferable which suggests the residual origin of this specific kind.

Residual breccias develop especially on Karst topographies where the limestone of the country rock contains cherty beds. Under long denudation the surface with its characteristic sink-holes and closed valleys comes to be covered in places to some depth with breccia of sharp-edged chips of flint, and this by submergence may be incorporated into the sequence of the geologic formations.

[1] W. S. Smith and C. E. Siebenthal, *U.S. Geol. Surv., Geol. Atlas*, Joplin Folio (148), p. 9.

The residual breccia of the Joplin district of Missouri has been described by Winslow,[1] Smith and Siebenthal,[2] and others. The breccia-producing rocks are Mississippian limestones rich in chert. At the close of the Mississippian the region was uplifted and, under long subaërial erosion, developed a typical Karst topography mantled with angular cherty waste. During early Pennsylvanian times the area was deeply submerged; the Carboniferous sea transgressed, but without either leveling the relief or assembling and rounding the residual cherts. The matrix is largely supplied by the sea-clays of the Cherokee formation. The residual breccia thus formed suffered further changes. Solution of the underlying limestone has caused the breccia to founder, producing complex brecciation and intermingling blocks of the country rock. Groundwater has also introduced a matrix of lead and zinc ores and jasperoid silica.

Talus breccia.—Accumulating at the foot of cliffs, from fragments broken off by frost and temperature changes, talus breccia is a rubble of sharp-edged fragments, wedge-shaped in radial section, and quite devoid of bedding. Stratification may be rudely simulated, since slabs and other unequiaxed blocks creeping and sliding down the slope come to rest with their longer axes parallel with the surface. Owing to greater inertia, the larger blocks may gather at the base. Small fragments prevail, but blocks of some considerable size may be supplied by local sapping. The matrix (the finer material derived from the weathering of the cliff and of the talus) is interstitial and lithologically identical with the fragments. Some of the matrix, however, may be foreign—dust and sand brought in by wind, humus of a soil cover, and travertine deposited by springs issuing from the cliff's base.

Talus breccias are local and extremely limited in width. Even under an arid climate favoring the perpetuation of cliffs, even in the hamada desert, where long lines of marching cliffs form the high risers for the broad steps of rock plateaus, talus accumulations are rapidly consumed by deflation and are but a few rods wide. The material is local and there is no zonal arrangement of fragments of different lithologic kinds.

[1] Arthur Winslow, *Missouri Geol. Surv.*, VII (1894), 464 f. [2] *Op. cit.*, p. 9.

An example of a talus breccia is described by Wilson[1] as occurring at the base of a cliff of Keweenawan sandstones covered by a sheet of ancient diabase.

Rock-glacier breccia.—A subspecies of talus breccia is that produced by rock glaciers, talus glaciers, or rock-streams, as they are variously known.[2] Talus may be very rapidly produced where the wedgework of frost is especially efficient, as in cold climates, on the lofty walls of cirques composed of rock that favors fragmentation by close jointing, or other structures. Under the urge of its own weight and that of the expansion of interstitial ice talus creeps forward from the feeding cliff in long tongues of waste which in shape somewhat resemble glaciers. Rock-glacier breccia differs from talus breccia only in its greater extension normal to the cliff, in the movement of the material to greater distances and with very gentle slopes, and in the fact that unequiaxed blocks may be expected to be found set at all angles, owing to the movement of material *en masse*.

The famous limestone breccias of Gibraltar, described by Ramsay and Geikie,[3] are attributed to this class. These breccias occupy wide tracts about the base of the Rock of Gibraltar and reach a thickness of at least 100 feet. Their slope in places does not exceed two or three degrees. The fragments are almost invariably quite angular. They vary in size from grit up to blocks 12 feet or more in diameter, and are distributed without regard to size and shape. They are no larger at the base of the cliffs than on the outskirts of the formation. The matrix is earthy and cements the breccia into firm rock. The authors cited attribute fragmentation to the work of frost under far severer climatic conditions than now obtain. The assemblage of the breccia by gravity in ordinary talus is negatived by the extent and slope and apparently by the set of the fragments. The angularity of the fragments, their size, and their lack of sorting preclude the theory of transportation

[1] A. W. G. Wilson, "Trap Sheets of the Lake Nipigon Basin," *Bull. Geol. Soc. Am.*, XX, 207–9.

[2] Whitman Cross and Ernest Howe, *U. S. Geol. Surv., Geol. Atlas*, Silverton Folio, p. 25; S. R. Capps, "Rock Glaciers in Alaska," *Jour. Geol.*, XVIII, 359–75.

[3] A. C. Ramsay and James Geikie, *Quar. Jour. Geol. Soc. London*, XXXIV, 505–41, 1878.

by torrential streams upon detrital slopes. It is concluded that heavy trains of débris saturated by meltings of thick snows have moved *en masse* down the steep slopes and out over the lower grounds below. The junior author reaffirmed this theory in 1881 and compared the breccia directly with the talus glaciers of the Rocky Mountains.[1]

A matter perhaps less satisfactorily explained is the frequent brecciated aspect of the undisplaced limestone of the Rock of Gibraltar. In the words of the authors cited, "In many places the Rock looks as if it had been smashed up *in situ*, the broken fragments having been subsequently consolidated by infiltration." The authors prove that the shattering is not due to faulting, and attribute it to frost. The fractures recall, however, those of the country rock of the landslide area of the Rico Mountains, referred by Cross[2] to prehistoric earthquakes of exceptional violence. Indeed, the features of the Gibraltar breccias as described by Ramsay and Geikie are not inconsistent with an origin in landslides, which also move out over gentle slopes and carry large fragments to the outer limits.

Landslide breccia.—Breccias of this class owe fragmentation in large measure, and assemblage wholly, to the force of gravity. In *rock-falls* the movement is sudden and violent, and the rock is shattered to pieces by successive impacts. Rock-fall breccia is a chaotic mixture of blocks, large and small, set at all angles and sharply angular. In the few seconds of the tremendous downrush of perhaps millions of tons of rock, the fracture of the masses to smaller and still smaller fragments and their crush to powder go on so rapidly that comparatively little opportunity seems to be given to the rounding of edges by attrition. The matrix consists of chinkstone and pulverized material and may embrace a contribution of soils and subsoils swept up by the rock-torrent.

Large rock-falls on steep slopes obtain sufficient momentum to carry them a considerable distance over gentle and even reversed gradients at the mountain's base. In the Elm rock-fall of 1881

[1] James Geikie, *Prehistoric Europe* (London, 1881), p. 219.

[2] Whitman Cross, "Geology of the Rico Mountains, Colorado," *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 149.

the landslide mass, after reaching the foot of the mountain, poured down the level valley floor for nearly a mile, covering it over its whole width to a depth of more than 30 feet.[1] The section of a rock-fall breccia taken normal to the cliff therefore resembles that of the rock-glacier. No marked difference in the size of fragments in different parts of the area covered has been recorded, so far as the writer is aware. In the breccia formed by the landslide at Frank, Canada, in 1903, described by McConnell and Brock,[2] large rocks are said to be common everywhere.

In rock-fall breccias, fragments are of local derivation and of a limited number of kinds of rock. No zonal arrangement is possible in a single slide; but where repeated falls occur, the earlier bringing down material from higher horizons on the mountain and the later falls material from lower terranes, zonal arrangements both vertical and horizontal may result. Thus Howe[3] explains the zone of rhyolite which forms the outer rim of the Pierson Basin rock-stream in Colorado, while the center of the mass consists of fragments of andesite of a lower volcanic series.

In *rock-slides* the movement is gradual and repeated. The displaced mass, therefore, is not so completely broken up as in the rock-fall, nor does it come to cover so large an area, except under special conditions. No type of breccia contains such large blocks as this. While the largest blocks of the Frank rock-fall measured 40 feet, blocks 300 feet in diameter occur in the Rico rock-slides, and in the profounder displacements of the adjacent telluride quadrangle one block of more than two miles in length has been described.[4] On the north side of the Grande Ronde River, Idaho, the Columbian lavas supply slidden blocks half a mile in length.[5] The breccia of rock-slides is characterized by the confused relations of the slipped blocks, their varying dip

[1] Sir W. M. Conway, *The Alps from End to End* (Westminster, 1895), 3d ed., p. 246.

[2] R. G. McConnell and R. W. Brock, *Ann. Rept. Dept. of the Interior, Canada*, 1903, Part VIII.

[3] Ernest Howe, "Landslides in the San Juan Mountains, Colorado," *U.S. Geol. Surv., Prof. Paper 67*, p. 34.

[4] Whitman Cross, *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 146.

[5] I. C. Russell, *U.S. Geol. Surv., Water Supply Paper 53*, p. 76.

and strike, their fissured and shattered condition, and their merging in places into rubble breccia of small fragments due to the breaking up of the blocks either by the force of the original slide or by that of later movements. A diagnostic may be found in the inward dip of the blocks, as noted by Russell.[1] Owing apparently to friction with the surface, the sliding blocks tend to rotate backward on axes normal to the slope and thus come to rest with a marked dip toward the cliffs from which they were derived. On the other hand, blocks creeping down talus maintain a dip parallel with the slope. The upper surface of both rock-fall and rock-slide breccias is hummocky, but this feature will hardly be preserved excepting where the landslide fell into deep water.

Bajada breccia.—The rugged mountains of arid regions are commonly fringed with wide slopes of rock-waste called bajada. Like those of talus, the fragments of the bajada have been detached by mechanical weathering. But unlike other subaërial breccias, the bajada has been aggregated largely by intermittent streams. Its fragments have been more or less water-worn. It forms an imperfect breccia and yet is far from being a typical conglomerate of well-rounded pebbles. The streams which build the bajada have certain peculiarities which greatly lessen the wear on the stones they carry. The long accumulated waste on the mountain slopes swept down by spasmodic rains loads so heavily the temporary streams of the barrancas that they have been designated as mud-flows.[2] In the washes and on the lower unchanneled slopes of the bajada the viscosity of the flow is further increased by absorption of the water by the thirsty sands. In the moving mass of the mud-flow, stones such as are carried in mountain torrents of humid climates as the bottom load and dashed against one another and the stream bed are here intermingled with the finer waste held in suspension, and are thus protected from mutual abrasion. Hence pebbles remain imperfectly rounded even to the outer edge of the bajada slope.[3]

[1] I. C. Russell, "Geology of the Cascade Mountains in Northern Washington," *U.S. Geol. Surv., 20th Ann. Rept.*, Part II, p. 19.

[2] For a graphic description of a mud-flow in the Himalayas see Sir W. M. Conway, *Geog. Jour.*, II (1893), 291.

[3] R. D. Oldham, *Quar. Jour. Geol. Soc. London*, L (1894), 469.

Unlike all other subaërial breccias, the bajada is stratified, and unlike that of marine and ordinary fluviatile conglomerates, the stratification is imperfect. The bedding is often local and ill-defined. Unsorted beds pass both vertically and horizontally into those well sorted. All this follows from the nature of the building-streams. Leaving the barrancas of the mountains and debouching on the gentler slopes, they suffer a sudden arrest of velocity as well as diminution of volume by the absorption of their waters. These checks are often enough to cause them to throw down their load, fine and coarse alike, with little or no sorting. The attitude of unequiaxed fragments of mud-flows on bajadas has not been sufficiently observed. It may be inferred from the method of their carriage that they will not always take the position of repose and that even flat stones may be left at any angle.

A bajada breccia is wedge-shaped, but on a larger scale than that of talus. Furthermore, there is a gradual decrease in size and angularity of the material in passing from the thick to the thin end.

The matrix of the bajada consists of the finer stream-wash and of dust and sand contributed by the wind. Beds of rubble breccia with interstitial matrix pass into endostratic breccias of predominant matrix and sporadic fragments. A characteristic matrix is a chemical deposit of lime carbonate by calcareous evaporating water. As in the Tintic mining district, Utah,[1] the material may thus be cemented into compact rock in which roofs and walls of deserted tunnels remain standing for years untimbered. The limy matrix may whitewash the pebbles and, by filling the interstices, form beds of caliche.

Dry climate conditions are indicated further by the absence of carbonaceous deposits and by the complete oxidation of iron compounds, the interfingering of playa clays about the outer margin, and, under extreme aridity, the association of beds of salt and gypsum in the centers of the bolsons. Wind-carved pebbles may be found, and beds of the millet-seed sand of the desert. The presence of well-rounded sand grains in a breccia, however, is a criterion to be used with intelligent caution. Desert sand once

[1] G. W. Tower and G. O. Smith, *U.S. Geol. Surv., 19th Ann. Rept.*, Part III, pp. 668–69.

shaped retains its form indefinitely. Thus the St. Peter sandstone, whose grains were originally ground under desert winds, was spread by the Ordovician sea, and again supplied the material for the Sylvania sandstone of Michigan. Either of these sandstones could furnish desert sand to breccias of several different types.

Bajada breccia is of local derivation; far-traveled stones from distant sources are not expected, yet the extent and complexity of the feeding-mountains may give the breccia great lithological heterogeneity. Ancient breccias are not necessarily associated with the buried mountains or uplands which supplied their waste. Such elevations may have been destroyed in the building of the bajada or by later denudation.

The Permian breccias of the Midlands, England, are now commonly regarded as of bajada origin.[1] They occur in rudely stratified, wedge-shaped masses, some more than 200 feet thick at one end and thinning out within four to eight miles. Beds of breccia are interstratified with current-laid sandstone and with marl, into which they graduate both vertically and horizontally. The fragments embrace a large variety of rocks and are now considered of local derivation. They are angular and subangular, more or less water-worn, but are never well rounded. Half a foot is a common measure of their size where they are largest. The matrix is calcareous or sandy.

Certain coarse breccias, intercalated with thin sandstone layers, in the Esmeralda formation of Nevada have been classified as detrital-slope breccias by Turner.[2] Examples well known to American students are the bajada breccias of the Newark formation.

Glacial breccia.—Subaërial glacier deposits are certainly to be classified as breccia, but their characteristics are so well known and so easily recognized, as a rule, that no description is considered needful.

[1] R. D. Oldham, *Quar. Jour. Geol. Soc. London*, L (1894), 463–70; W. W. King, *ibid.*, LV (1899), 97–128; T. G. Bonney, *ibid.*, LVIII (1902), 185–203.

[2] H. W. Turner, "Geology of Silver Peak Quadrangle," *Bull. Geol. Soc. Am.*, XX, 245.

Volcanic subaërial breccia.—Volcanic breccias laid in open air include:

1. Flow breccia, in which unrounded fragments have become incorporated in flowing lava, either from its frozen and broken crust or from material, volcanic, residual, or of other origin, overridden by the advancing stream.

2. Tuff breccia, made up of the fragmental products of explosive eruptions. The matrix consists of the finer materials of the eruption and in some instances has been washed in by mud-flows. Or the matrix may be formed by gangue and ore stuffs deposited in the interstices by heated waters. Tuff breccias often include fragments of the country rock torn from the sides of the duct below the base of the volcanic cone.

Subaqueous breccias.—Breccias accumulated under water may be divided into three general classes with the following subdivisions:

1. Breccias of subaërial fragmentation
   - *a*) and *b*) Subaqueous talus and landslide breccia
   - *c*) Raft breccia, deposits from rafts of ice (iceberg or ice floe), trees, or seaweed.
   - *d*) Desiccation breccia
   - *e*) Subaqueous volcanic breccia
2. Breccias whose fragmentation is the work of aqueous agencies or of agencies working in water
   - *a*) Shoal breccia
   - *b*) Reef breccia
   - *c*) Beach breccia
   - *d*) Tide-glacier and shore-ice breccias
3. Breccia whose fragmentation is due to internal stresses
   - *a*) Glide breccia due to overload, earthquakes, deformation, undercut

Talus and landslide subaqueous breccias.—These two varieties may be taken up together because of certain common features. Both consist of local beds of angular fragments from near-by sources, intercalated between younger sedimentary strata. Suitable topographic conditions for the formation of each are found in the fjords and rias of a rugged coast and in mountain lakes, especially Chelans, lying in oversteepened glacier troughs. The matrix is partly of the same material as the fragments and partly of infil-

trating sediments. It is generally interstitial, in contrast with the preponderant matrix of raft breccias, but about the margins blocks projected farthest may be found sporadic.

Talus and landslide breccias may be discriminated from each other by their characteristic profiles—the even and smooth slope talus and the hummocky surface of the landslide—by the longer extension of the landslide from the parent cliffs, and, in the following example, by the landslide tearing up the sediments of the sea-floor over which it moves and mingling them with its own débris.

The very interesting Jurassic breccia of the Ord, on Moray Firth, Scotland, is pretty certainly due to a landslide fallen into the sea.[1] The strata among which the breccias are imbedded consist of finely laminated shales with occasional thin seams of limestone. Hence the water in which they were laid was quiet, unvexed by powerful waves or currents. The littoral fossils—ammonites, corals, etc.—show that the deposits are marine and indicate the close proximity of the shore. This is confirmed by numerous remains of cycads, ferns, and conifers apparently drifted in by rivers. Both fauna and flora prove the warmth of the climate and forbid the assumption of an ice raft as the means of transportation. The breccia is contemporaneous with the Jurassic beds in which it lies, but it is not intraformational, since its fragmental material is derived from the Old Red Sandstone which occurs in the immediate vicinity. The fragments vary in size from chipstone to blocks 10 feet in diameter. The majority are sharply angular, some show signs of attrition on the edges, and not a few, especially those of smaller size, are completely rounded. They are heaped together in the wildest confusion. The upper surface of the breccia beds is irregular, and the strata deposited upon it show the influence of its projections. The breccias vary in thickness from a foot or two to 50 feet. The matrix is fossiliferous with contemporaneous Jurassic fossils in a more or less comminuted condition. In places are found numerous masses of Jurassic reef-building coral torn from their bases and heaped in all positions among the débris.

[1] J. W. Judd, "The Secondary Rocks of Scotland," *Quar. Jour. Geol. Soc. London*, XXIX (1873), 187–95; J. F. Blake, "On a Remarkable Inlier among the Jurassic Rocks of Sutherland," *ibid.*, LVIII (1902), 290–310.

All these phenomena are explained by landslides descending from the steep slopes of Old Red Sandstone hills or mountains into the quiet waters of a Jurassic fjord or ria and depositing on the even-layered silts the tumultuous beds of breccia. The débacle would sweep up rounded pebbles from the beaches, tear corals from their bases, crush shell banks in the estuary, and mingle their débris with the fragments of the slides. That earthquakes were the cause of these great rock-falls is suggested by the contemporary sandstone dikes found in the district.[1]

It may be added, if only in illustration of the diverse interpretations held of breccias, that Murchison[2] described these breccias as due to crush incident to the upheaval of neighboring granite. Blake[3] argues the deposit of an ice foot. Huddleson, in the discussion of Blake's paper, postulates ocean currents strong enough to tear up masses of corals and to gather and distribute old shore accumulation of talus, although ocean currents, even if powerful enough to transport the immense blocks of the breccia without wear of edges, are not so paroxysmal as to heap them in the midst of the fine silts of quiet water. Judd[4] recognizes the cataclysmic nature of the formation and suggests very tentatively river-floods of the most violent character. Yet the floods of a river cannot be expected so to maintain their energy on entering the ocean as to deposit their bottom load in water of considerable depth and to mingle it with detritus torn from the ocean floor. The momentum of the rock-fall would seem to be the only force capable of the work, and this origin is advanced by Woodward[5] and by Teall[6] in the discussion of Blake's paper.

Raft breccias.—In breccias of this class the fragments have been transported in such a way as to escape wear *en route.* Angular fragments of such soft rocks as shale and talcose, schists and limestone, brought unworn from distant sources, prove that the carriage was upon the surface of the ocean, and not by wave and current along the ocean floor. Further evidence of surface trans-

[1] H. B. Woodward, *Quar. Jour. Geol. Soc. London,* LVIII (1902), 206.

[2] *Transactions Geol. Soc. London,* Ser. 2, Vol. II, Part II, p. 293.

[3] *Op. cit.* [4] *Op. cit.* [5] *Op. cit.*

[6] *Quar. Jour. Geol. Soc. London,* LVIII (1902), 205.

port should be looked for in disturbances in the bedding of the inclosing strata. Laminae beneath the larger stones may be bent down, and the succeeding laminae may show the influence of the projecting blocks, thus proving that the fragments were dropped through some depth of water. Confirmation has been found in the position of fragments with the heavier ends downward.

Raft breccias are endostratic and the fragments are sporadic. There may also be an irregular distribution of them—in places a huddle of fragments where the unloading of the raft was sudden. Some blocks may be quite too large for wave and current carriage.

Rafts capable of transporting the material of breccias are either of ice or of vegetation. Ice rafts include both icebergs and shore ice in the form of floes, or of the ice-foot.

Iceberg breccia.—Since the iceberg is detached from the tide glacier, iceberg breccia is composed of the material of the ground moraine. In a larger or smaller proportion the fragments prove their derivation by their subangular form and striated faces. A considerable lithologic variety is to be expected, since the parent glaciers usually drain a large extent of country. Transport from distant sources has long been looked upon as evidence of iceberg carriage, since icebergs drift farther than other rafts.

In weighing the evidence of iceberg breccia, and of glacier breccia as well, it is often necessary to discriminate glaciation of pebbles from slickensides by earth movements which affect the mass of the formation. In favor of glaciation is the incrustation of planed or striated surfaces by marine organisms, such as serpula or shells, since these surfaces must have been produced before the deposit of the pebbles in the breccia beds.[1]

Striae may be considered "rutsch striae" produced after the deposit of the breccia under the following conditions: (1) when they occur on matrix as well as pebbles; (2) when they are found on different planes below the surface of the pebbles; (3) when they affect traceable planes or zones of shear; (4) when the striae of different pebbles in the same plane run in the same direction and

[1] I. C. Russell, "Second Expedition to Mt. St. Elias," *U.S. Geol. Surv., 13th Ann. Rept.*, p. 25; W. J. Sollas and A. J. Jukes, "Included Fragments of the Cambridge Upper Greensand," *Quar. Jour. Geol. Soc. London*, XXIX (1873), 11–15.

correspond in direction with earth movements recorded in adjacent strata; (5) when the number of striated pebbles in different parts of the breccia varies directly with the amount of shear; (6) when the striae on faulted pebbles end at the fault plane; (7) when the striated surface is covered with films deposited from solution. Several of these diagnostics are mentioned by Marr[1] as characteristic of scored pebbles having the form of glacial bowlders in an English breccia. Tectonic breccias often display slickensided blocks,[2] but they are hardly liable to be confounded with glaciated pebbles. It may be added that the proportion of glaciated pebbles in iceberg breccias may be exceedingly small in comparison with that in the drift-sheets of far-traveled continental glaciers.

Iceberg breccia, as well as any other, may be sheared after its formation. In this case neither slickensides nor glaciation can be used to disprove the other process. A dual origin seems to be indicated in scored pebbles of some of the Permian breccias of England, but there are students who claim that they are due to earth movements only.

Shore-ice breccias.—In arctic regions shore ice often receives a load of angular waste, and, drifting along the coast or out to sea, desposits it as breccia amid the sediments of the ocean bed.

The ice-foot, described by Feilden and De Rance[3] as having its origin chiefly in snows drifted into water offshore, receives the waste of the talus slopes at whose base it lies. Ice floes along shore also obtain a load of similar débris tobogganing out from talus slopes and falling upon the floes from sea-cliffs. Shore ice may also carry rounded beach pebbles frozen to its base and glaciated pebbles shaped by the grinding of ice pans on shelving shores in storms and under the action of the tide.

The Quebec group of the Ordovician of Canada contains breccias explained by Sir J. William Dawson as early as 1833 as due to shore

[1] J. E. Marr, "Notes on a Conglomerate near Melmerby," *Quar. Jour. Geol. Soc. London*, LV (1899), 11–13.

[2] E.g., the Wapsipinicon breccias of Iowa, W. H. Norton, *Iowa Geol. Surv.*, IX, 447–48.

[3] H. W. Feilden and C. E. de Rance, "Geology of the Arctic Coasts," *Quar. Jour. Geol. Soc. London*, XXXIV (1878), 563–66.

ice.[1] These breccias are very irregular in their distribution and vary rapidly and greatly in their thickness. The fragments are of Cambrian limestone and of the lower limestones of the Quebec group. "The only means of explaining these conglomerates seems to be the action of coast ice . . . . which seems to have had great reefs of limestone, probably in the area of the Gulf of St. Lawrence, to act upon and to remove in large slabs and bowlders, piling these up on banks to constitute masses of conglomerate." Walcott also postulates floating ice in the absence of any other explanation in accounting for bowlders in certain intraformational conglomerates, saying: "No other explanation occurs to me that will account for the transportation of a bowlder from the shore line and the placing of it upon the sea-bed so as not to disturb to any marked degree the sediments then accumulating."[2]

The bowlder beds of the Talchir group of India are attributed to ice rafts by Oldham.[3] Sporadic bowlders from distant sources and reaching a maximum diameter of 15 feet are distributed with extreme irregularity in distinctly stratified shales and sandstones. Large numbers occur within limited tracts, but over many square miles of the area they are quite absent. Where the sedimentary matrix is laminated, the laminae bend down beneath and arch over the included blocks. As the fragments are far too abundant and widespread to have been carried by rafts of vegetation, floating ice remains the only possible vehicle. This inference is confirmed by the presence in two localities of striated pebbles, although most of the fragments are distinctly water-worn. The various phenomena of the Talchir beds point to their accumulation in large inland water bodies covered with ice in winter, to which torrential streams led down steep valleys and to which glaciers locally descended.

Tree-raft breccia.—Uprooted trees, drifted down to sea on river-floods, may carry for some distance out from shore angular stones

[1] Sir J. W. Dawson, "On the Eozoic and Paleozoic Rocks of the Atlantic Coast of Canada," *Quar. Jour. Geol. Soc. London*, XLIV (1888), 809–910, quoting an earlier paper.

[2] C. D. Walcott, "Intraformational Conglomerates," *Bull. Geol. Soc. Am.*, V, 197.

[3] R. D. Oldham, *Geology of India*, 2d ed., pp. 157–60.

of the waste mantle and of the weather-broken rocks beneath, firmly held entangled in the meshes of their roots. The fragments may be expected to be smaller than those of the ice raft. Fine waste is absent from the breccia, since it is soon washed out of the interlacing roots of trees when immersed in river or sea. Since the fragments are derived from the zone of weathering, decomposed and etched surfaces and weather-rounded edges may be looked for, especially in fragments made of the more soluble rocks.

Seaweed breccia.—The buoyant power of seaweeds and the tenacity with which they adhere to rock are well known. They are thus able to transport stones so small that they would readily escape from the roots of floating trees. At the Orme's Head, North Wales, angular fragments of limestone have been found attached to the roots of Laminaria.[1] The stones which seaweed commonly carry are the well-worn shingle of the pebble beach. But angular stones may be transported by them when fragments are broken by the battering of waves from the rocky reefs on which seaweeds grow.

A pudding breccia occurring in one or two localities near Dublin, Ireland, has been attributed to tree rafts by Jukes[2] and to carriage by seaweed by Ball,[3] although earlier observers had invoked rafts of floating ice. The matrix is highly fossiliferous, encrinital, carboniferous limestone. The fragments, sharp-edged, sporadic, small, are of granite and metamorphic rock outcropping in the neighborhood. The small size of the fragments lends some weight to seaweed as the transporting agent.

Desiccation breccia.[4]—Surface layers of unconsolidated fine-grained sediments, such as clay or limy mud, when exposed to the air, dry, shrink, and sun-crack. The angular blocks of this mosaic may again be covered with water and imbedded in the sediments which it throws down. The conditions for desiccation breccia are afforded where there are long intervals between periodic

[1] C. E. de Rance, *Quar. Jour. Geol. Soc. London*, XLIV (1888), 374.

[2] Jukes, *Manual of Geology* (1886), p. 298.

[3] V. Ball, *Quar. Jour. Geol. Soc. London*, XLIV (1888), 371–74.

[4] Desiccation conglomerates is a term proposed by J. E. Hyde, *Amer. Jour. Sci.*, 4th ser., XXV, 400 f.

floodings, as in the shallow lakes of arid basins and those of river flood-plains and in lagoons cut off from sea except at highest tide or greatest storms. Desiccation breccia may be only as thick as the sun-cracked layer. Where the dried blocks of the mosaic or pieces of their upturned edges are assembled by the waves, the fragments may be irregularly piled in rubble and should show some wear. The matrix differs little from the fragments, and the breccia is endostratic. A special variety is playa breccia. The cracks of the sun-baked clay of the dried-up lake bed may be filled with desert sand, and this accumulates also beneath the curled-up edges of the cakes. Desiccation breccias have been described from the Algonkian of Idaho by Ransome and Calkins,[1] and designated as "mud breccias." The angular or slightly rounded fragments are of argillite and are imbedded in a somewhat coarser-grained and more arenaceous matrix. Sun-cracks are found in direct connection, and the angular fragments are supposed to be broken off from the edges of flakes of mud curled up by drying in the sun.

Volcanic subaqueous breccia.—Volcanic breccia deposited under water may be distinguished from that laid on land by the sediments on which it rests and by the bedding of the tuff. Subaqueous tuff breccias, as remarked by Leith,[2] are distinguished only with very great difficulty from water-laid clastics resulting from the erosion of volcanic rocks.

Shoal breccia.—In this class of submarine breccias, and in reef and beach breccias as well, disruption and assemblage both are caused by waves and tides. The normal action of these agents is to round and sort the coarser stuff they handle and to deposit it in well-defined conglomerates. It is only under exceptional conditions that they can assemble beds of fragments so little worn as to constitute a breccia.

Shoal breccia is formed by the action of waves and tides on shoals due to diastrophic movements or to general aggradation. In reef breccia, on the other hand, there is proof that the shallows permitting wave-pluck are due to local upbuilding of the sea-floor.

[1] F. L. Ransome and F. G. Calkins, "Geology and Ore Deposits of the Cœur d'Alene District, Idaho," *U.S. Geol. Surv., Prof. Paper 62*, p. 31.

[2] C. K. Leith, *Structural Geology* (New York, 1913), p. 66.

Shoal breccias are commonly of limestone. Calcareous sediments rapidly harden by cementation, and may be broken into breccia by waves which under identical conditions merely redistribute the grains and particles of unindurated sands and clays. On shoals of calcareous sediments lying partly above and partly below the plane of effective wave-erosion, waves and tides tear up the cemented beds of the elevations and deposit fragments in the hollows safe from further wear.

In the case of the extensive sheets of brecciated limestone of the Galena and the Niagara formations of Wisconsin, Chamberlin[1] has suggested that the tide may have played an important rôle. Under a large tidal oscillation storm waves may be brought at low tide within reach of the surface of shoals which, except at this brief interval, remains below wave-base. Fragments torn at low tide by storm waves, and the finer waste stirred into suspension, thus have time to settle back together as fragments and matrix of a breccia, and, it may be added, to be further protected by a cover of other sediments before a low tide again coincides with a heavy storm and the process is repeated.

Strong tides working on shoals are postulated by Lane[2] in explaining the limestone breccias of the Salina and Lower Helderberg of Ohio. The prevalence of ripple-marks, mud-cracks, brecciated and conglomeratic layers, leads to the inference of a great flat which seems to have been just awash. "If we imagine tides like those of the Bay of Fundy rushing over this flat, producing this breccia and conglomerate . . . . we have the conditions of the Helderberg on Monroe deposits."

In explaining the foundations of Mississippian reefs in Yorkshire, England, Tiddeman[3] infers local deformations which here and there brought the sea-floor above wave-base. As a result, shoals were formed of wave-plucked angular and more or less rounded fragments on which colonizing corals and mollusks reared their reefs. In a similar way certain Algonkian breccias of Idaho are explained by Ransome and Calkins.[4] "It is supposed that in the

[1] T. C. Chamberlin, *Geology of Wisconsin*, I (1883), 168–69.

[2] A. C. Lane, *Geol. Surv. of Michigan*, V (1895), Part II, p. 27.

[3] R. H. Tiddeman, cited by Marr, *Quar. Jour. Geol. Soc. London*, LV (1899), 330.

[4] *Op. cit.*, p. 38.

vast mud flats upon which the St. Regis beds were being laid down, the surface was raised up into a low dome of small extent upon which the soft strata were exposed to wave action and fragments were broken away and incorporated with the soft siliceous mud that was then accumulating in the surrounding waters."

Reef breccia.—Reefs with brecciform structures may be built by corals, calcareous algae, and molluscous shells. Coral breccia, the variety most common and most closely studied, is produced in several different ways. As a coral reef is built up toward low-tide level, the interspaces between the masses of growing coral are filled with broken fragments of coral branches and the finer waste of the reef. The coral framework is brittle and is further weakened by boring worms and mollusks; hence the accretion of broken branches goes on below the zone of wave-wear, and the fragments remain angular. After wave-base is reached, accretion proceeds still more rapidly, and now the other rim of the reef, the belt of its most active growth, acts as breakwater and protects the inner portions of the coral fields from the wear of the surf. Thus is formed *reef-rock breccia* or coralline rag, a well-cemented limestone in which masses of coral retain the attitude and position of growth, and to which the varied animal and vegetal life of the reef contributes.

In this reef-rock waves cut the channeled and cavernous rock-bench. The fragments plucked from the bench are swept inland by heavy storms over and beyond the beach of coral sand, and cover large tracts with lichen-blackened fragments, angular to such a degree that both Dana[1] and Sollas[2] have compared them to the rough clinkers of lava which strew the slopes of Mauna Loa and of Etna. Intermixed is wave-worn and wind-blown coral sand, which acts as a matrix, cementing the *breccia of the island rock.* By slow subsidence these deposits may be carried beneath the surface of the sea. The upgrowth of the rim of the reef meanwhile protects them from being worked over by the waves and thus the brecciated stucture is preserved.

A third variety of coral breccia accumulates at the foot of the steep outer face of the reef, where angular fragments torn by waves

[1] J. P. Dana, *Corals and Coral Islands* (New York, 1879), p. 178.

[2] W. J. Sollas, *Age of the Earth* (London, 1905), chapter on Funafuti, p. 108.

from the growing corals of the rim come to rest below wave-base. Such a breccia, at the foot of reefs of Mississippian limestones in Great Britian, has been described by Tiddeman.[1]

The characteristics of coral breccia may be enumerated:

1. Like all wave and tide breccias, coral breccia is either a rubble or a pudding breccia. Crackle and mosiac breccias are not to be expected.

2. The matrix consists of the fine detritus of the reef.

3. Both matrix and fragments are singularly devoid of siliceous and argillaceous impurities. An exception occurs in reefs which receive more or less waste from an adjacent land.

4. Reef-rock breccia may show little or no trace of bedding. In the core of the deep boring of the Funafuti atoll, which passes through this rock to a depth of 1,114 feet, the only stratification found was that due to such irregular accumulation of detrital material as occurs between and around the corals.[2] The numerous Silurian reefs of Wisconsin and Iowa show little or no trace of bedding from top to bottom, while areas occur within them of conglomeratic or brecciated structure.[3] In the case of the wave-driven fragments of the island rock some sorting and bedding with low dips are to be expected, and the talus formed below the reef probably shows rude layers dipping outward at the angle of repose.

5. The fragments of coral breccia show varying amounts of wear. Least worn are fragments of reef rock accumulated below wave-base. The island rock necessarily approaches a conglomerate in the rounding of its constitutent masses. How short a time and distance are needed to destroy the angularity of fragments is seen in a photograph and description by Kent[4] of the result of a single tropical hurricane of a few hours' duration in 1884. A fringing reef was wrecked and its fragments, swept inland, were piled above reach of the highest tides. Massive head-corals were torn up and rolled together like the small pebbles of the beach and ground down to subspherical symmetry.

[1] R. H. Tiddeman, *Rept. British Soc.* (Newcastle-on-Tyne), p. 602.

[2] Judd, quoted by Sollas, *op. cit.*, p. 128.

[3] T. C. Chamberlin, *Geology of Wisconsin*, I, 184; W. H. Norton, *Iowa Geol. Surv.*, IX, 424; XI, 307.

[4] Saville Kent, *Great Barrier Reef of Australia*, pp. 50–52.

6. Coral breccia is intimately associated with stratified deposits of coral mud and sand and pebbles. The reef contains stretches of barren sand within the outer rim. The island is bordered by a beach of sand and shows extensive tracts of sand in the interior. Soundings disclose belts of sand with which the talus of the reef must interfinger. Fine-grained limestones are forming in the lagoon and in deeper offshore waters.

7. Fragments may themselves be brecciform. Complex brecciation occurs especially where fragments of the reef-rock breccia are carried inland to form the island rock.

8. The chief diagnostic of an ancient coral breccia is the presence of the reef proved to be the work of corals by its fossils. Thus the classification of the breccia of the St. Louis formation of southeastern Iowa and adjacent parts of Missouri and Illinois as a coral breccia is held untenable by Bain[1] because of the absence of reef-building corals. On the other hand, brecciated structures connected with coral reefs are not necessarily of coral origin. Associated with the Silurian reefs of Iowa are local breccias unquestionably due to the later deformation of beds of limestone accumulated upon the flanks of the coral mounds.

Beach breccia.—On beaches where wave-action is inefficient and angular blocks are supplied as from sea-cliffs, a deposit of fragments so little worn as to be classed as breccia according to prevailing usage may result under conditions of rapid submergence. In all cases, however, more or less wave-wear will be found upon the fragments, and the deposits, like other subaqueous deposits of both angular and rounded material, should perhaps be termed a breccia-conglomerate.

The St. Louis breccia of southeastern Iowa, classified by Gordon[2] as reef breccia, is considered by Bain[3] a shore formation in which blocks of limestone up to 4 feet in diameter were torn from their beds and buried in sands apparently at the foot of a series of cliffs. Savage[4] also finds evidence of vigorous wave-action and a close

[1] H. F. Bain, *Iowa Geol. Surv.*, V, 150.

[2] C. H. Gordon, "On the Brecciated Character of the St. Louis Limestone," *Am. Naturalist*, XXIV (1890), 305–13; *Jour. Geol.*, III, 289 f.

[3] H. F. Bain, *Iowa Geol. Surv.*, V, 150.

[4] T. E. Savage, *Iowa Geol. Surv.*, XII, 263 f.

proximity of the shore. The subaqueous origin of the breccia is confirmed by Van Tuyl,[1] but only in part. The first period of disturbance was one in which, under violent wave-action, mounds of shoal breccia were produced. The major disturbances, however, are of later date and gave rise to tectonic breccias associated with mashing, folds, and overthrust faults.

Tide-glacier breccia.—Tide glaciers, laying their loads on sea-bottom, give rise to breccias which prove their parentage by faceted and scored pebbles of a considerable variety of rocks and by subjacent disturbed sedimentary deposits or glacier pavements where the ice has overridden the sea-floor. Associated stratified beds with littoral fossils prove the breccia submarine. Icebergs detached from the glacier front extend the formation seaward in an ice-raft breccia, with a lessening proportion of morainal stuff.

The Chaix Hills, described by Russell,[2] are carved from an uptilted block 4,000 or 5,000 feet thick, composed of morainal material and sea-clays. The fragments of this breccia are sporadic throughout the terrane from base to summit. They are both angular and rounded and reach a diameter of some 8 feet. Lithologically they are as various as are the bowlders of the moraines of the living glaciers of the encircling mountains. Sea-shells of living species are numerous in the finer portions, which are largely made of glacier silts.

Glide breccias.—The sediments of the sea-floor are subject to slow and rapid gravitational movements, comprehensively termed glides, which deform, shatter, and brecciate the involved strata. Glides may be expected to affect the steeper slopes, such as the sides of submarine channels, the front of deltas, and the edges of continental shelves. They are known to have taken place on slopes as low as about three degrees. The mobility of marine deposits is increased by permanent saturation and frequently by lack of cementation.

Subaqueous glides may be classified according to their chief precipitory causes as *overload* glides, *earthquake* glides, and *deformation* glides.

[1] F. M. Van Tuyl, "Brecciation Effects in the St. Louis Limestone," *Bull. Geol. Soc. Am.*, XXVII, 122–24.

[2] I. C. Russell, "Second Expedition to Mt. St. Elias," *U.S. Geol. Surv., 13th Ann. Rept.*, pp. 24–26.

Overload glides: On land, gravitational movements occur on slopes due chiefly to erosion; on the sea-floor unstable equilibrium must often result from aggradation. Sediments are unequally spread owing to set of current and distance from sources of supply. Deltas and banks are thus built up, until along their edges overload gives rise to facial shear and glide.

Earthquake glides: The chief geologic effect of earthquakes on land is to precipitate movements both of the waste mantle and of the solid rock beneath. Alluvium on valley floors lurches toward the thalweg, the waste on hillsides, slumps and avalanches, and even solid rock may be intimately shattered and shaken down in landslides of the first magnitude.[1] The effects of earthquakes on marine deposits must be of similar nature and proportionally great. Evidence collected by Milne[2] proves conclusively the fact of subaqueous glides and their close connection in a number of instances with earthquakes. Since the continental delta throughout geologic time has been the zone, not only of sedimentation, but also of great diastrophic movements of which earthquakes are an expression, it may be assumed that earthquakes have been a not uncommon cause of glides in geologic history. Yet no instance is known to the writer in which a glide breccia has been assigned to this precipitory cause. The most direct evidence pointing to such an origin is to be found in contemporaneous associated faults or sandstone dikes. Since earthquakes recur in the same area for long periods of time, earthquake-glide breccias may recur at successive horizons in a formation on in a sequence of formations.

Deformation glides: There is some reason to believe that within the continental delta deformation may so accent the slope that glides of unindurated sediments result. In explaining the Devonian breccia of Iowa, McGee[3] offered as "a useful even though a far-fetched hypothesis" that of an elevation at the close of the Devonian by which the declivity was increased, a consequent slight

[1] *The California Earthquake of April 18, 1906*, I, Part II, pp. 384 f. (Carnegie Institute, 1908); Darwin, *Voyage of a Naturalist* (London, 1891), p. 220; Whymper, *Travels amongst the Great Andes*, IV (London, 1892), 260; Whitman Cross, "Geology of the Rico Mountains, Colorado," *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 149.

[2] John Milne, "Suboceanic Changes," *Geog. Jour.*, X, 129–46, 259–85.

[3] W. J. McGee, "Pleistocene History of Northeastern Iowa," *U.S. Geol. Surv., 11th Ann. Rept.*, p. 323.

settling seaward of the fresh-formed Devonian sediments upon the sloping flanks of the Island of Wisconsin, and a slipping of the strata upon one another causing crumpling, buckling, and brecciation. The same cause is assigned by Hershey[1] for a very local breccia near Galena, Missouri. Minor causes of subaqueous glides are erosion and undercut of submarine banks by springs and currents.

The characteristics of glide breccias are due to the deformation, to the shear and crush of the gravitative movement, and not to its precipitory cause. Hence all the varieties mentioned are alike in structure and have a close resemblance to endolithic breccias caused by deformation.

The fragments are contributed by any layers hard enough to suffer fracture. They may be sharply angular or somewhat worn by mutual attrition. They may be apposed in crackle and mosaic breccias, or disposed in rubble, according to the amount of movement. Fragments may show by their relative positions the initial attitude of the layer before fragmentation. These breccias are likely to graduate into folded structures with parallel and thickened axes and common dips, and the fragments of beds bent before breaking may show flexures and contorted laminae. A zonal arrangement is to be looked for where strata differing lithologically and of a considerable thickness are involved.

The matrix is supplied by the least indurated or most readily comminuted beds, especially by the surface sediments as yet unconsolidated, and by any bottom layer which by its plasticity determines the base plane of the glide. Thus shales furnish matrix to fragments broken from brittle limestones. Matrices evidently pasty and fragments somewhat plastic at time of brecciation point to subaqueous brecciation either by glide or by wave-action, and the former alternative is to be chosen when there are proofs of folding before fracture. This test applies only when brecciation in the zone of flow and fracture is precluded. The relative amount of matrix and fragments is determined by the volumes of strong rock and weak rock involved and by the violence of the movement. Even a breccia of sporadic fragments may result.

[1] O. H. Hershey, "A Devonian Limestone Breccia in Southwestern Missouri," *Science*, N.S., I, 676–78.

Overlying beds are undeformed or share only in later deformations affecting the entire body of the strata. Their contact is accordant where the breccia has been reworked and leveled by wave-action. In this case they contain at bottom fragments of the broken beds, either rounded to a conglomerate or partially angular and forming a pudding or rubble breccia. If the slidden mass is reassembled below wave-base the contact is discordant and superincumbent beds are free from fragments. The breccia may thus be either endostratic or have the hummocky upper surface of a landslide. Glide breccias may graduate laterally as well as vertically into sedimentary beds. They rest on undisturbed strata of earlier date. Endostratic breccias passing within the limits of the same stratum into folded laminae point strongly to an origin in glide. A complete section of a glide and the associated strata would show, according to Heim,[1] the following relations: in the area bared by the glide, (1) a reduction of the number of strata as compared with the adjacent areas, (2) local disconformity without time interval; in the area on which the glided mass came to rest, (3) increase in the number of strata, (4) superposition of older on younger beds, (5) displacement of facies. Glides involving subaqueous and subaërial sediments have occurred in a number of instances on the shores of the Swiss lakes, in Sweden, and along the Black Sea.[2] In the lower Devonian limestones of Gaspe a bed has been described by Logan[3] whose structure is evidently due to subaqueous glide. This bed, 7 feet thick, is made up of several thin layers of limestone and limy shale, wrinkled, contorted, and in places brecciated, while the associated beds are free from marks of deformation.

The edgewise position of broad, flat pebbles in evenly bedded strata near Bellefonte, Pennsylvania, has been attributed by Brown[4] to subaqueous glide.

Endolithic breccias.—Of breccias formed within the lithosphere the following classes may be distinguished: (1) tectonic breccia (dynamic, pressure, friction breccia), due to crustal movements

[1] Quoted by A. W. Grabau, *Principles of Stratigraphy* (New York, 1913), p. 660.

[2] Grabau, *op. cit.*, pp. 657 f., 779 f.

[3] Sir W. Logan, *Geology of Canada* (1863), pp. 391 f.

[4] T. C. Brown, *Jour. Geol.*, XXI, 241–42.

and produced by lateral or vertical pressure or by tension; (2) expansion breccia (caused by increase of volume due to chemical change); (3) founder breccia (ablation, solution breccia), due to the foundering of strata, usually because of the ablation by solution of the supporting beds.

Tectonic breccia.—Three varieties are discriminated: fault breccia, fold breccia, and crush breccia. In the latter, brecciation is accomplished without either faulting or folding except so far as the rupture planes of the breccia may be considered as minute faults.

Fault breccia: Here fragmentation is due either to friction along the fault plane or to distributive ruptures associated with the major fault, and due to shearing stresses. In stratified rock, fault breccias associated with both normal and reversed faults are easily recognized, since the zone of brecciation crosses the planes of bedding. Friction breccias along bedding faults are more difficult to distinguish. Here one must seek for proofs of lateral displacement in slickensides with polish, scorings, and seams of "gouge" (clays formed by grinding). Local breccias of this variety have been identified by Ransome[1] in the Rico Mountains of Colorado.

Complex brecciation is not uncommon, since repeated movements along the fault plane shatter and drag a breccia already formed and firmly cemented with perhaps vein stuff and ore. Breccia zones running parallel with the main fault may show but slight displacement. Thus in the San Francisco district of Utah such breccia zones in brittle quartzite pass downward into monoclinal folds in shale.[2] The rocks on opposite sides of a fault plane may be differently affected—granite, for example, may be sheared and the limestone opposite brecciated.[3] Fault breccias often form aquifers for mineralized waters which deposit matrices of ore and gangue. Many breccias of this class have been brought to notice because of their economic importance.

[1] F. L. Ransome, "Ore Deposits of the Rico Mountains, Colorado," *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 297.

[2] B. S. Butler, "Geology and Ore Deposits of the San Francisco, etc., Districts, Utah," *U.S. Geol. Surv., Prof. Paper 80*, p. 72.

[3] W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana," *U.S. Geol. Surv., Prof. Paper 75*, p. 151.

Fold breccia: Under suitable conditions of load and stress beds may fold by means of minor fractures. Cross and parallel fracture planes develop, and under increasing stress the fragments are rotated and displaced. The folded bedding is more or less completely destroyed and there results a mosaic or even a rubble breccia. Where the rock is compressed joints or fissility ruptures are produced. A rising anticline develops radial tension cracks along the convex surface as soon as the deformation passes the limit of elasticity of the rock. In the experiments of Willis[1] the first fractures of the arching strata occurred at points of sharpest curvature—along the axial plane at the summit of the anticline and on radial planes of shear at its base. A basal weak stratum, compelled to rise beneath a competent stratum as the latter was bent upward, accommodated itself to the change by shear, resulting in complete brecciation.[2] Here the breccia occupied the center and base of the anticline, while the competent upper beds remained at first unbroken and later under increased pressure were ruptured by a stretch thrust fault.

The degree of folding necessary for brecciation varies with the rigidity of the stratum, with load, and with the amount and rapidity of application of the stress. Even limestone and granite under slight load yield plastically and bend to a perceptible degree when the stress is very slowly applied.[3] On the other hand, brittle rock under presumably sudden stresses breaks into breccia when the deformation has not exceeded a gentle warping.[4] Under the same strain and load different rocks fold or break according to their elasticity. Among sedimentaries the most brittle and therefore the most liable to brecciate are cherts, some shales, and calcilutites; among metamorphic rocks, quartzites, graywackes, and rather siliceous slates. A thin layer of chert may be seen broken into a string of angular bits within a layer of limestone which shows no

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Pls. 75, 76.

[2] *Ibid.*, Pl. 93.

[3] Arthur Winslow, *Am. Jour. Sci.*, 3d ser., XLIII, 133–34; H. F. Bain, *Iowa Geol. Surv.*, VIII, 378.

[4] Smith and Siebenthal, *U.S. Geol. Surv., Geol. Atlas*, Joplin Folio, p. 9.

other trace of yielding. In the breccias of the Wapsipinicon stage of the Iowa Devonian, a thick, tough, crystalline-granular coquina is normally broken into large slickensided blocks which retain something of the flexures into which the bed was thrown, while subjacent thinly laminated calcilutites are shattered to a jumble of small fragments.[1]

Shales yield plastically under load, but when near the surface and under sudden stress they easily crush to breccia. Shales promote the fragmentation of inclosing and especially of included beds of other rocks. Thus the Wapsipinicon breccias of Iowa embrace the Independence shale and its associated limestones. In the zone of fracture and flowage, alternate thick layers of brittle and of plastic rock may produce brecciated beds, alternating with folded layers, whose arches may be truncated by the movement of the fragments of the rigid and brecciated beds.[2]

Unlike glide breccias, breccias due to folding are included between strata which have shared the brecciating deformation according to their competency. But since any sort of breccia may be involved along with the associated terranes in a later deformation further proof of origin must be looked for in the remains of initial folded structures in the breccia. A certain continuity may be traced from fragment to fragment, showing clearly that the fragments are constituent parts of a flexed and broken layer. The breccia may graduate into folds. Where the breccia involves beds of different kinds of rocks, anticlines and synclines may sometimes be traced in a zonal arrangement of the crushed material.[3]

Crush breccias: The sheet breccias of the Joplin district, Missouri, illustrate how terranes of brittle rock may be brecciated by lateral pressure without any further mass deformation than that exhibited in gentle warpings. Heavy ledges of chert have been thoroughly and finely crushed in places and cemented by a chemical deposit from ground-water. The fragments are of small size and are thus in direct contrast with the residual breccias of a higher

[1] W. H. Norton, *Iowa Geol. Surv.*, IV, 158–61.

[2] C. R. Van Hise, "Principles of North American Pre-Cambrian Geology," *U.S. Geol Surv., 16th Ann. Rept.*, Part I, p. 681.

[3] W. H. Norton, *Iowa Geol. Surv.*, IV, 165.

horizon in the same area. The breccia is endostratic and often of the crackle or mosaic type, with fragments rotated but slightly in the ledge.[1]

In all tectonic breccias the fragments are left of sharpest edge at time of breaking, and a universal sharp angularity points strongly to a tectonic or to other endolithic origin. Yet the fragments may be worn by grinding one upon another in the zone of shear and thus become so completely rounded as to be readily mistaken for the pebbles of a wave-laid conglomerate. Thus are produced the "pseudo-conglomerates" of Van Hise.[2] The rounding of pebbles of a conglomerate, however, is pretty uniform for pebbles of any given size, the smaller being better rounded than the larger. Moreover, the conglomerate graduates into finer sedimentary deposits. The rounding of the fragments of a pseudo-conglomerate is fairly uniform for any given portion of the brecciated zone. Tracts where fragments are well rounded regardless of size pass into tracts where all the fragments are angular.[3] Dale[4] has noted that angular pebbles of soluble rock in an insoluble matrix may be later rounded by the dissolving action of acid ground-water. It may be added that by solution under pressure fragments develop salients and re-entrants, wholly different from either fracture planes or rounding by attrition or solution. Fragments may also show in flexed and contorted laminae evidence of the strain to which their layers were subjected. Such distortion phenomena imply considerable plasticity in the layers, although it was finally exceeded by the strain. Contorted laminae may also be seen in the fragments of breccias originating in subaqueous glides, where the plasticity of the sediment is due to imperfect lithification.

The form and size of the fragments of tectonic breccias so far as due to fracture depend on the amount of stress, the closeness of joints and bedding planes, and the natural fracture of the rock. Thus in one of the experiments of Willis[5] fault planes divided a

[1] Smith and Siebenthal, *U. S. Geol. Surv., Geol. Atlas,* Joplin Folio, p. 9.

[2] Van Hise, *op. cit.,* p. 679. [3] *Ibid.,* p. 680.

[4] T. N. Dale, "Structural Details in the Green Mountain Region," *U.S. Geol. Surv., 16th Ann. Rept.,* Part I, p. 569.

[5] *Op. cit.,* Pl. 93.

brecciating layer at first into rhombs bounded by two faults and two bedding planes, and afterward, under increasing pressure, into triangular forms bounded by two faults and one bedding plane. From brittle, thin-layered rocks under slight stresses quadrangular and subquadrangular small fragments are derived. The sharpest edges are found in rocks of conchoidal fracture, minutely faulted into triangular fragments.

The matrix when contemporaneous is supplied by the material of the weaker beds involved and by wear and tear of the stronger beds. It graduates from powder and angular sand, the product of attrition, to chinkstone, approaching the size of the smaller fragments. When the interstices are left at time of brecciation more or less unfilled, as is likely to be the case, a veinstone matrix of travertine, of jasperoid, or of iron compounds is often deposited later by ground-water. Such a matrix weighs against any origin, e.g., subaqueous glide, which is not likely to leave unfilled interstices. The significance of both veinstone and attrition matrices lies also in the proof they offer that sedimentary deposits had no access to the zone of brecciation.

The material of tectonic breccias, with the exception of the matrix of chemical deposit, derives from the geologic formations of the beds involved. Fragments of beds belonging stratigraphically below the base of the breccia cannot be included in it. On the other hand, in subaqueous or subaërial breccias fragments deriving, for example, from cliffs of Archean rock may be deposited as Devonian breccia on Devonian lands or in Devonian seas. But while in subaërial and subaqueous breccias the matrix is never older than the fragments, in tectonic breccias an older and weaker terrane may supply the attrition matrix, in which the fragments of a younger superjacent stratum are imbedded. Where beds of different rocks are involved zonal arrangement is sometimes traceable, which at once excludes the breccia from many varieties of subaqueous and subaërial origin. A tectonic breccia does not rest, like subaërial breccias, upon an erosion surface. It cannot graduate upward into strata inclosing sporadic fragments. An important diagnostic may be found in undisturbed areas, perhaps of very large size, which have transmitted the strain instead of yielding to it by fragmentation.

Expansion breccia.—Fragmentation may be caused by increase of bulk of the brecciating rock or of associated layers which transmit the pressure to it. Expansion may be caused by recrystallization or by hydration. Expansion breccias graduate into folded structures, but the folds show quaquaversal deformation, the *enterolithic* structure of Grabau,[1] a term translating the "Gekröse" of Koken, and this intestinal coiling may serve to distinguish them and the associated breccias from folds and breccias due to lateral pressure.

Founder breccia.—Where beds of soluble rocks have been in part or whole removed by the chemical action of ground-water, founder breccias of the superincumbent beds are produced on a scale commensurate with the extent of the ablation. All terranes between the dissolving foundation and the surface of the ground or some competent superior stratum are affected by the process. Characteristic features are abnormal dips, sag folds without parallelism of axes, areas of crushed rock alternating with horsts where the strata are undisturbed. The matrix may be of crushed material of the same terrane as the fragments. In this case it is likely to be small in amount and insufficient to cement the breccia firmly, for the attrition of the fragments in founder is probably much less than in tectonic brecciation. The matrix may be a later chemical deposit.

The fragments show only the small wear due to mutual attrition. Like other endolithic breccias, a founder breccia can carry no water-worn pebbles. It is conceived that founder breccias of thick extensive beds include larger blocks than any other type of breccia excepting that due to landslide. Certainly they may be far too great for detachment by waves or by mechanical weathering and for fragmentation under lateral pressure. Horsts may be difficult to discriminate from the undisturbed areas of tectonic breccias.

Thin-shale founder breccias have been described by Ransome[2] in the blankets of several mines in the Rico district, Colorado. The blanket of the Enterprise mine, for example, is an unconsolidated breccia of shale from 2 to 20 feet thick, resting on a thin

[1] *Principles of Stratigraphy*, p. 757.

[2] F. L. Ransome, "Ore Deposits of the Rico Mountains, Colorado," *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 273 f.

bed of light-gray earth, shown by chemical analysis to be a residuum of gypsum.

The Monroe breccia of Michigan is considered by Hindshaw[1] to be of this type, although Lane[2] has classified it as a shoal breccia and Grabau[3] as a rock-stream or rock-glacier breccia, at least in its outcrops at Mackinac Island and the vicinity. As observed by the writer, the breccia at this locality is a rubble, entirely without bedding, of angular fragments set at all angles and varying in size from gravel up to blocks 25 and 30 feet in length. Fragments and matrix are of soft buff magnesian limestone, and the latter is usually interstitial. Occasional seams of calcite and celestite occur. In certain areas a zonal arrangement of material is seen in the prevalence of chert, showing that the material of the breccia has not been intimately mingled as in subaërial breccias whose fragmentation is due to weathering. A still more conclusive negative to such an origin is given in areas of rock quite undisturbed, such as a block extending eastward along the cliffs for upward of 200 feet from the eastern border of the park at Mackinac. This observation is confirmed by Rominger,[4] who states that "frequently large rock-masses composed of a series of successive ledges which have retained their original position to each other are scattered through the breccia." The wide distribution of the breccia in Michigan and Ohio precludes any local origin. The size of the fragments and the absence of water-wear are considered inconsistent with a subaqueous origin. Along the eastern shore of the island, however, numerous talus blocks show endostratic brecciation. Laminae flexed and faulted and partially brecciated are imbedded in a matrix of the same material and maintain more or less of their original parallelism with each other and with the bedding of the stratum. In the undisturbed block at the east of the park at Mackinac sporadic fragments occur toward the base of massive beds. These phenomena imply disturbed sedimentation, or sub-

[1] *Michigan Geol. and Biol. Surv. Publ. 14,* Geol. Ser. 11, pp. 206–7.

[2] A. C. Lane, *Geol. Surv. Michigan,* V, Part II, p. 27.

[3] A. W. Grabau, *Science,* N.S., XXV, 295–96; *Principles of Stratigraphy,* pp. 547–48.

[4] Carl Rominger, *Geol. Surv. Michigan,* I, Part VI, p. 27.

aqueous glides, at the time of the deposit of the limestone, but the main brecciation is taken to be of later date.

There is also seen an association with folds which suggests either a tectonic or a founder breccia. The underlying red and blue shales seen in the rock bench about the island rise in places as anticlines in the sea-cliffs. On the cliffs east of the fort at Mackinac, beneath a cornice of about 15 feet of horizontal massive beds, appears a zone, 9 feet thick, of thin-bedded limestone, thoroughly crackled, with unhealed seams, shattered, and in places with the fragments rotated and displaced, but with the bedding still traceable to a large extent. In places low folds can be made out with a height of 8 inches and width of some 4 feet, a deformation apparently adequate to brecciate this brittle rock.

The theory of founder presupposes the removal by solution of beds of rock salt and gypsum underlying the red and blue shales on which the limestone rests. These shales are not commingled with the breccia of the limestone. If the breccia is due to founder, it must be concluded that the soft clay shale yielded plastically to unsupported pressure of overlying beds without mixing with the fragments into which these beds were broken. In places small chimneys of breccia penetrate the shales beneath, and the ledges of breccia which rise in reefs above the country rock of shale in the low ground of the north of the island may have a like relation.

The grounds on which Hindshaw's theory of founder is supported are as follows:[1] The Monroe formation rests on the Salina, which includes beds of salt, in places 800 feet in thickness, and of anhydrite partially changed to gypsum. The Monroe itself contains beds of anhydrite. In the Monroe beds and in the overlying Dundee limestone, which is also involved in the brecciation, the circulation of ground-water is exceptionally active. Discordant and abnormal dips occur, accountable for by slumping due to solution of the Salina beds about their outer edges.

Cavern breccia is a local variety of founder breccia. Detached masses fall from the roof and sides of a cave and accumulate on the floor as breccia, which may come to fill nearly the entire space. Cavern breccias may sometimes be recognized by their shape as

[1] *Op. cit.*, pp. 206–7.

casts of the irregular chambers and chimneys of caverns whose walls remain as molds. Cave earth, bone breccia, incorporated fragments of stalactites, and stalagmitic crusts may certify the origin. The matrix is either of travertine or of limestone sand and cave earth.

Campbell[1] has described a cavern breccia exposed in the walls of a canyon near Fort Stanton, New Mexico, and suggests that the frequent repetition of the process might result in complete brecciation of certain beds more soluble than the rocks above and below.

Cavern breccias are common in the lead and zinc mining regions of the Upper Mississippi Valley. Fragments of sheets of ore mingle with the dolomite débris. The matrix may be metalliferous, giving rise to sprangle ores. Slight foundering of the strata above caverns has produced crackle breccias whose fissures are healed with Smithsonite.[2]

Pseudo-brecciation.—This term is used by Wallace[3] to designate irregular mottlings due to partial dolomitization. Various other causes produce irregular mottlings, but such can hardly be mistaken for brecciation structures.

[1] M. R. Campbell, "Origin of Limestone Breccias," *Science*, N.S., XXVII, 348.

[2] Whitney, *Geology of Iowa*, I, 448; A. C. Leonard, *Iowa Geol Surv.*, VI, 11 f.; S. Calvin and H. F. Bain, *ibid.*, X, 480 f.

[3] R. C. Wallace, *Jour. Geol.*, XXI, 420–21.

REVIEWS

Stratigraphy of the Pennsylvanian Series in Missouri. By HENRY HINDS and F. C. GREENE. Missouri Bureau of Geol. and Mines, Vol. XIII, 1915. Pp. 407, figs. 5, pls. 32, map 1.

This volume treats chiefly of the stratigraphy, paleontology, and lithology of the barren formations of the Pennsylvanian series in this state, thus supplementing Vol. XI, which deals primarily with the coal deposits.

The subdivisions now recognized in the series are given below:

Group	Formation
Missouri	Wabaunsee Shawnee Douglas Lansing Kansas City
Des Moines	Pleasonton (unconformity in) Henrietta Cherokee

The formations in this classification are differentiated into 30 members which might be called formations by those who give the Pennsylvanian the rank of a system. The system is markedly unconformable on the beds beneath, and its upper members are the youngest consolidated rocks in the state.

The Des Moines and Missouri groups were differentiated originally with the belief that the latter contained much greater quantities of limestone. The only basis now recognized is a rather well-marked faunal break. There are rather strong indications of a widespread unconformity in the Pleasonton, and this faunal break may be related to it. If this is found to be true the plane between the two groups will be drawn at the unconformity. There has been much confusion in the nomenclature of the Pennsylvanian of this area owing to duplication of names and miscorrelations. That considerable progress has been

made in correcting this situation is indicated by the fact that the classification of this report has been approved by the United States Geological Survey and is now official for the state surveys of Kansas, Iowa, and Nebraska with one minor exception in each of the last two states.

Lithologically, the series is made up chiefly of shales alternating with limestones. Sandstones, clay, and coal are found in lesser quantities. Most of the lithologic units are quite persistent laterally, but a few are notably lenticular. The broader features of the present structure have resulted from two periods of folding since the close of the Pennsylvanian. The first of these developed monoclinal dips to the west and northwest and the second formed a number of narrow anticlines with associated synclines. The axes of these folds are markedly parallel and trend northwest-southeast throughout the state. These are shown on a structure contour map drawn on the basis of rather meager data.

Invertebrate paleontology is the subject of an exhaustive chapter by Dr. Girty. More than 250 collections containing more than 350 species form the basis of his report. The species are listed by localities and by zones for each formation, and the valuable data of these lists is made available more readily by a composite table showing the range of each species. Descriptions and illustrations are given of a number of species that are new or have been called into question. Paleobotany is discussed in a short chapter by David White.

Some progress has been made in correlating the Missouri series with eastern areas. Paleontological evidence indicates that the lower part of the Cherokee is of Pottsville age and the upper part is basal Allegheny. It is suggested on the basis of incomplete collections that Allegheny time extends to the unconformity in the Pleasonton and that Conemaugh time ends well up in the Shawnee.

The writers of this valuable report did not fail to include a chapter of bibliography which includes all the important publications consulted in its preparation.

W. B. W.

The Red Iron Ores of East Tennessee. By Ernest F. Burchard. Bull. Tenn. Geol. Survey No. 16, 1913. Pp. 173, pls. 17 (including 5 maps), figs. 30 (including 6 maps).

The purpose of this report is to describe and explain the origin of the red iron ores as they occur in the Cumberland Plateau and the Great Valley in east Tennessee.

It is not possible to give a generalized section of the strata in east Tennessee because of the local variations in the sequence. The ores are contained chiefly in the "Rockwood" formation (Silurian). They are found also in the Tellico sandstone (Ordovician) and to a very minor extent in the Grainger shale (Devonian and Mississippian). Two widespread formations, the Knox dolomite (Cambrian and Ordovician) and the Chickamauga limestone (Ordovician), occur below the Tellico and "Redwood." The Chattanooga shale (Devonian) and the Newman limestone (Mississippian) which lie above the "Rockwood" are important, the former as a reference horizon for the "Rockwood" ore and the latter as a source of the limestone for fluxing material in the iron industry.

In general the beds of the Cumberland Plateau are nearly horizontal, while those of the Great Valley are tilted, folded, and faulted.

The term iron ore as used in this report includes that which runs 20 or more per cent metallic iron. The red ores consist essentially of hematite; the impurities are calcium carbonate, silica, alumina, magnesium carbonate, sulphur, phosphorus, and manganese.

The Tellico ore varies from a ferruginous sandstone to lenses of compact rich ore. The deposits near Riceville, near Sweetwater, and east of Knoxville (here the ore is dominantly limonite) are described; the two last mentioned are residual deposits.

The "Rockwood" formation is composed of lenses of sandstone, shale, limestone, and hematite; its thickness varies from a few feet to over 1,000 feet. The ore beds are mainly in the upper 60–200 feet. The ore is "a mixture of fossil fragments and flaxseed-shaped grains." The soft ore (due to the leaching of calcium carbonite from hard ore) carries 40 to 58 per cent metallic iron, while the hard ore runs from 25 to 45 per cent metallic iron. It is believed "that the 'Rockwood' iron ore was formed by the deposition in a body of water of sediments containing iron, together with calcium carbonate, silica, alumina, and other minerals in minor proportions." Later much of the calcium carbonate of the fossils was replaced by iron oxide; this may have occurred even before the consolidation of the strata and "it probably involved only the original sediments." The "Rockwood" ore outcrops more or less continuously along the base of the Cumberland escarpment and in the Tennessee Valley; the total linear exposure, if only a single seam is taken into account, is 245 miles, of which 60 miles is workable hard ore.

Central east Tennessee is the most productive area in the state.

Underground (slope and adit) mining is carried on almost exclusively.

"Notes on the Iron Industry" conclude the report.

V. O. T.

Geology and Coal Resources of North Park, Colorado. By A. L. Beekly. U.S. Geol. Survey, Bull. 596, 1915. Pp. 118, pls. 12.

North Park is described as a synclinal basin limited on the east and west by anticlinal mountain ranges, on the south by a high ridge composed of Tertiary extrusives, and on the north by an area of pre-Cambrian crystalline rocks faulted up into contact with the Paleozoic and later sediments of the Park. The latter comprise two sharply distinct groups: the lower, which rests upon pre-Cambrian crystallines, begins with a few feet of limestone of doubtful age, at the base of the Red Beds, and ends with the Pierre shale—7,400 feet of beds in all, apparently conformable throughout; the upper group comprises some 5,000 feet of uppermost Cretaceous or Eocene strata included in the Coalmont formation. The folding of the region took place in part prior to the deposition of the Coalmont and in part later. Moderately extensive faulting accompanied or followed the later folding, and therefore affected the Coalmont in common with the older rocks. Lying upon the Coalmont in uncertain relationship is the North Park formation, a 600-foot series of clastic sediments interbedded with sheets of pyroclastic volcanics. The Tertiary igneous rocks near the southern border of North Park occur in both intrusive and extrusive relations. Andesine basalt and volcanic agglomerate are the chief types. Granite is the chief constituent of the pre-Cambrian complex exposed in the mountains east, west, and north of the Park.

Coal occurring in the lower part of the Coalmont formation is the one mineral resource of this area which is now being exploited. More than two billion tons of sub-bituminous coal are estimated as the available reserve. The coal seams are of unusual thickness, one bed reaching a thickness of more than 50 feet, and maintaining an average thickness of 30 feet along a 15-mile outcrop.

C. W. T.

Common Minerals and Rocks: Their Occurrence and Uses. By R. D. George. Bull. Colo. State Geol. Survey No. 6, 1913. Pp. 406, pls. 5.

The main purpose of this bulletin is to describe the commoner minerals and rocks, and furnish the means of recognizing them and knowing their uses.

V. O. T.

The Iditarod-Ruby Region, Alaska. By HENRY M. EAKIN. Bull. U.S. Geol. Surv. No. 578, 1914. Pp. 45, pls. 6 (including 4 maps), fig. 1.

The Iditarod-Ruby region is situated in west-central Alaska between the headwaters of the Iditarod and the Yukon at Ruby.

The geologic succession is as follows: probable Paleozoic metamorphic rocks; Cretaceous sedimentary and volcanic rocks; post-Cretaceous intrusives; Quaternary unconsolidated deposits that include glacial material.

Conglomerates (in places several hundred feet thick), the material of which has been derived from the underlying metamorphic rocks, occur principally near the base of the Cretaceous beds. Some contain bowlders up to 3 feet in diameter.

Placer gold, with a minor amount of silver, is the mineral resource of the region. The gold has been derived chiefly from quartz veins (which are probably genetically related to the post-Cretaceous intrusions) that traverse the igneous, sedimentary, and metamorphic rocks.

The value of the gold and silver produced in 1912 in the Iditarod, Innoko, and Ruby districts was respectively \$3,500,000, \$250,000, and \$150,000.

In 1913 the value of the winter production in the Ruby district was \$102,200, while that of the summer production was estimated at \$750,000.

V. O. T.

The San Franciscan Volcanic Field, Arizona. By HENRY HOLLISTER ROBINSON. Professional Paper, U.S. Geol. Survey, No. 76, 1913. Pp. 213, pls. 14 (including 2 maps), figs. 36 (including 8 maps).

The San Franciscan volcanic field embraces an area of about 3,000 square miles in north-central Arizona.

Chap. i is devoted to the geography of the region.

Chap. ii treats chiefly of the sedimentary formations and structure. The sequence of sedimentary rocks is as follows: the Mississippian and Pennsylvanian Redwall limestone; the Pennsylvanian Supai formation ("Lower Aubrey" sandstone and shale), Coconino ("Upper Aubrey") sandstone, and Kaibab ("Upper Aubrey") limestone; the Permian(?) Moencopic formation (red to light-brown shales, with some sandstone and calcareous layers); the Triassic "Lithodendron formation" (basal

conglomerate, sandstone, shales, and "marls") and "Leroux formation" (shales, with some sandstone and calcareous beds); and Quaternary moraines and alluvium. The thickness of this generalized section is about 2,500 feet. An unconformity occurs between the Kaibab and the Moencopic, between the latter and the "Lithodendron formation," and between the Triassic and later rocks. The Moencopic formation is a fluviatile or shallow-water deposit; the Triassic beds are continental deposits. The major structural feature of the region is a very flat anticline which trends N. 30° W.

Chap. iii gives detailed descriptions of the volcanoes and lava fields. Three general periods of volcanic activity are recognized: (1) widespread basaltic eruptions from small cones, (2) eruptions of lavas (andesites to rhyolites) to form a few large cones, and laccolithic intrusions, (3) extrusion of basalt (less widespread but more cones built up than in the first named). San Francisco Mountain, which is the principal feature of the area, is composed of "lavas and breccias belonging to five distinct stages of eruption."

"The Geologic History of the Volcanic Field and Adjacent Country" is given in chap. iv. The volcanic activity of the first period occurred in the late Pliocene after the peneplanation of the region, that of the second period took place in the early Quaternary during or after the mature dissection of the area, and that of the third period during the latter part of the Quaternary subsequent to broad regional uplift. There was folding and flexing during the latter half or at the close of the Eocene. Faulting occurred at the close of the Miocene, at the close of the Pliocene, and during the middle or latter part of the Quaternary.

The last two chapters, v and vi, are devoted respectively to petrography and petrology.

V. O. T.

Transactions of the American Institute of Mining Engineers. Vol. L. New York, 1915. Pp. 1008.

Material for this volume was presented at the Pittsburgh meeting in October, 1914. Three topics include the major portion of the volume: (1) iron, geology, and metallurgy; (2) coal and coke with by-products; and (3) petroleum. The volume contains less purely geological matter than either of the preceding volumes for the year. Fifty-two papers and discussions, many of which are illustrated, are included.

A. D. B.

Triassic Life of the Connecticut Valley. By RICHARD SWANN LULL. Connecticut Geol. and Nat. Hist. Survey, Bull. 24.

The author interprets the environment, both physiographic and climatic, of Newark time in the Connecticut valley, and gives a full discussion of the animal life with descriptions and illustrations of both the fossils and the trails and footprints in these beds.

The remarkable thing about this fossil field is that actual fossils are exceedingly scarce but trails and footprints are found in marvelous abundance. In actual fossils the invertebrates are represented by only two species of *Unio* and a single aquatic insect species. The terrestrial vertebrate skeletons are all reptilian, consisting of only two species of phytosaurs, two of aëtosaurs, and five of theropod dinosaurs.

However, the trails and footprints indicate a much greater and more varied fauna. Of the invertebrates, annelids, insects, spiders, scorpions, and fresh-water crustaceans of great variety were doubtless present. The footprints represent two, possibly three, classes of terrestrial vertebrates—amphibia of salamandrine form and also stegocephalians; among the reptiles, lizards, turtles, and dinosaurs, and possibly, also, rhynchocephalians, phytosaurs, aëtosaurs, and theromorpha. There is no evidence that birds were present.

C. H. E.

The Cretaceous-Eocene Contact in the Atlantic and Gulf Coastal Plain. By L. W. STEPHENSON. Professional Paper, U.S. Geol. Survey, No. 90-J, 1915. "Shorter Contributions to General Geology, 1914." Pp. 155–81, pls. XI–XIX (including 2 maps), figs. 13–20 (including map).

"The Cretaceous deposits of the Atlantic and Gulf Coastal Plain are separated from the overlying Eocene and younger formations by an unconformity of regional extent"; the unconformity can be traced from New Jersey to the Rio Grande, and from there southward into Mexico.

After the Upper Cretaceous sediments were laid down, the sea withdrew to the south and east some distance beyond the present shore-line; the Lower Eocene beds were deposited on a nearly base-leveled surface.

The faunal changes that occurred between the deposition of the uppermost Cretaceous and the lowermost Eocene strata were very profound; out of 168 species representing 89 genera in the *Exogyra costata* zone, which includes the upper part of the Selma chalk (uppermost Cretaceous), 20 or more common genera and practically if not all of the

species became extinct before the Midway group (lowermost Eocene) was deposited. Stephenson quotes T. W. Vaughan as follows: "The changes that took place in the marine animal life of the Atlantic and Gulf Coastal Plain during the time represented by the unconformity separating the Cretaceous and Eocene of this area are more striking than the changes that have taken place between earliest Midway time and the present day. . . . ."

V. O. T.

The Stratigraphy of the Montana Group, with Special Reference to the Position and Age of the Judith River Formation in North-Central Montana. By C. F. Bowen. Professional Paper, U.S. Geol. Survey, No. 90-I, 1915. "Shorter Contributions to General Geology, 1914." Pp. 95–153, pl. 1.

The area treated in this report "lies east of the Big Snowy and Judith mountains and extends from Musselshell, on Musselshell River, to Judith, on Missouri River, Mont." The generalized section of the sedimentary rocks in ascending order is as follows: *Cretaceous*: Colorado shale (thickness not measured), Montana group (Eagle sandstone) (200–300 feet), Claggett formation (700± feet), Judith River formation (250–500 feet), Bearpaw shale (1,100± feet); and the *Eocene*(?) Lance formation (700–800 feet). There is no evidence of an unconformity at any horizon in this section.

It is concluded that "the evidence of the vertebrate fauna, so far as in the present state of knowledge it has any weight, and the evidence of the fresh- and brackish-water invertebrates, so far as it is decisive for accurate time determination, indicate a closer relationship between the Belly River [of Canada] and Judith River than between either of these formations and the Lance. This is in accord with the stratigraphic evidence, which shows conclusively that both the Judith River and Belly River formations are separated from the Lance by amarine formation which is of undoubted Cretaceous age."

V. O. T.

Statistics of the Mineral Production of Alabama for 1913. By Charles A. Abele. Geol. Surv. of Alabama, Bull. 15. University, 1914. Pp. 67.

A compilation from Mineral Resources of the United States.

A. D. B.

The Coalville Coal Field, Utah. By CARROLL H. WEGEMANN. U.S. Geol. Survey, Bull. 581-E, 1915. Pp. 24, pls. 6.

The Coalville coal field lies about 30 miles northeast of Salt Lake City, in the valley of Weber River. High-grade sub-bituminous coal has been mined here for more than fifty years.

The report covers four townships. The rocks of the district include some 8,000 feet of shales and sandstones of Colorado and Montana (?) age, which are folded into a slightly overturned and pitching anticline, and are unconformably overlain by 1,000 feet or more of Wasatch conglomerate. Several transverse and nearly vertical faults of small displacement cut the gently dipping limb of the fold. Both the folding and the faulting took place chiefly in pre-Wasatch time, when considerable erosion was likewise accomplished; but weaker movement of both types appears to have followed the deposition of the Wasatch beds.

The one productive coal bed, known as the "Wasatch" bed, varies from 5 to 12 feet in thickness. This coal compares favorably in quality with several Wyoming coals. Coal occurs in thinner seams at two other horizons, 2,000 feet above and 850 feet below the "Wasatch" bed, respectively. All three horizons are in the Cretaceous system.

C. W. T.

Preliminary Report on the Clay and Shale Deposits of the Province of Quebec. By J. KEELE. Canada Dept. of Mines, Memoir 64. Ottawa, 1915. Pp. 280+iv, pls. XXXIV, figs. 13, map 1.

Describes the clay-bearing horizons and groups producing localities by the age of the clay produced. Particular emphasis is laid on the Pleistocene clays. A considerable portion of the memoir is devoted to the technologic aspects of the clay industries.

A. D. B.

"The Pebble Phosphates of Florida." By E. H. SELLARDS. *Florida Geol. Survey, Seventh Annual Report,* 1915, pp. 25–116.

In an earlier report this writer has discussed the origin of hard-rock phosphates, and this paper extends the study to land-pebble and river-pebble deposits. The land-pebble phosphates are found in the Bone Valley formation of late Miocene or early Pliocene age. They form a portion of a basal conglomerate laid down by a sea advancing over the Alum Bluff formation, a phosphatic marl of late Oligocene age. In this

marl the phosphate was in the form of pebbles and more finely divided material. As the result of a long period of erosion covering most of the Miocene, the phosphatic materials accumulated at the surface and were reworked by the Bone Valley sea. The river-pebble deposits have been formed in the beds of streams that have lowered their channels into either the Alum Bluff or the Bone Valley phosphate horizons.

W. B. W.

Lewis and Gilmer Counties. By DAVID B. REGER. West Virginia Geol. Survey, 1916. Pp. 660, figs. 12, pls. 30, maps 2.

Several volumes each year are added to the excellent county reports already published by this state. Lewis and Gilmer counties, located near the center of the state, have large coal deposits and are rich in oil and gas. Some of the largest gas wells of the Appalachian field were drilled in Lewis County.

The Pennsylvanian formations do not reach the development in these counties that is reported from areas to the south and west. The Pittsburgh seam of the Monongahela series carries the principal coal reserve, and the oil and gas sands range in age all the way from the Chemung to the Dunkard series.

W. B. W.

The Montana Group of Northwestern Montana. By E. STEBINGER. Professional Paper, U.S. Geol. Survey, No. 90-G, 1914. "Shorter Contributions to General Geology, 1914." Pp. 61–66, fig. 1.

The Montana group of northwestern Montana is composed of four conformable formations which are, in ascending order: the Virgelle sandstone (220 feet thick) which is chiefly marine, the Two Medicine formation (1,950 feet thick) which is mainly a fresh-water deposit, the marine Bearpaw shale (490 feet thick), and the brackish and marine Horsethief sandstone (360 feet thick). These formations are similar to those of the Montana group described in southern Alberta by Dawson, but differ decidedly from those in the central part of Montana. The Belly River series of southern Alberta is equivalent to the Virgelle sandstone plus the Two Medicine formation, and these in turn are equivalent to the Eagle, Claggett, and Judith River formations (of central Montana) combined.

V. O. T.

Supposed Oil-Bearing Areas of South Australia. By ARTHUR WADE. Geol. Survey of South Australia, Bull. 4, 1915. Pp. 54, figs. 12, pls. 3.

This bulletin gives the results of field search for oil-bearing horizons in four areas along the seacoast. The rocks in these areas are largely pre-Cambrian schists and quartzites either outcropping or concealed by a thin covering of Tertiary sediments. On Kangaroo Island are clastics assigned to the Cambrian, and glacial deposits doubtfully Permo-carboniferous in age.

The writer finds nothing in the lithology or structure of the strata that can be interpreted as favorable to oil accumulation. He believes that fragments of asphaltum found along the shore have come from beds down-faulted beneath the sea by the great fractures along the southern edge of the continent.

W. B. W.

Coal Fields of Kittitas County. By E. J. SAUNDERS. Washington Geol. Survey, Bull. 9, Pp. 204, figs. 52, pls. 38.

Kittitas County has led all the counties of this state in the production of coal for many years. The output is chiefly from a 19-foot vein in the Roslyn formation of middle Eocene age. The coal is of good bituminous grade and quite free from impurities. The general structural relations of the beds are quite simple, but there are many striking local exceptions, and some of these are illustrated by an excellent series of photographs and diagrams.

In certain portions of the county the Manastash formation of upper Eocene age carries coal beds that are of no commercial importance at present.

W. B. W.

Contributions to the Stratigraphy of Southwestern Colorado. By WHITMAN CROSS and ESPER S. LARSEN. Professional Paper, U.S. Geol. Survey, No. 90-E, 1914. "Shorter Contributions to General Geology, 1914." Pp. 39–50, pl. 1, figs. 2.

The overlap of the Gunnison formation (=La Plata sandstone (Jurassic) below + McElmo formation (Jurassic[?] (above) on pre-Cambrian rocks "extends at least 50 miles farther up the valleys of the Gunnison and Tomichi than was represented for the Jurassic beds on the Hayden map. . . . The relations in the Piedra Valley suggest that the La

Plata sandstone overlapped earlier sediments and came into contact with the pre-Cambrian rocks along a general north-and-south line, crossing the San Juan Mountains area." The pre-Dakota section of Piedra Valley is given.

V. O. T.

A Reconnaissance in the Canyon Range, West-Central Utah. By G. F. LOUGHLIN. Professional Paper, U.S. Geol. Survey, No. 90-F, 1914. "Contributions to General Geology, 1914." Pp. 51–66, pl. 1, figs. 4–8 (including map).

The Canyon Range in west-central Utah is formed almost wholly of lower Mississippian and older(?) limestone, and upper Mississippian and Pennsylvanian(?) quartzite, overlain unconformably by Eocene conglomerate. Pleistocene Lake Bonneville beds and, locally, later Quaternary deposits floor the valleys on either side of the range. "Volcanic rocks have been reported from the extreme northern and southwestern parts of the range, beyond the limits of the area visited."

V. O. T.

The History of a Portion of Yampa River, Colorado, and Its Possible Bearing on That of Green River. By E. T. HANCOCK. Professional Paper, U.S. Geol. Survey, No. 90-K, 1915. "Shorter Contributions to General Geology, 1914." Pp. 183–89, pls. 2.

Yampa River, which is one of the principal tributaries of Green River and empties into it from the east, is believed to be a superimposed stream whose present course was established after the deposition and emergence of the Browns Park formation (Eocene?). It is thought that "the assertions of the antecedent origin of Green River should be accepted only after more facts have been obtained bearing on the original extent and thickness of the late Tertiary formations, as well as on the diastrophic history of the Uinta Range."

V. O. T.

"The Gold-Bearing Gravels of Beauce Co., Quebec." By J. B. TYRRELL. *Bull. Am. Inst. Mining Eng.*, 1915, pp. 1–12.

Describes the placer deposits of the Chaudiere, Gilbert, and Des Plantes rivers. A point of physiographic interest is the suggestion of an Appalachian center of glaciation, from which the ice is thought to have moved northwestward over the area included in the report.

A. D. B.

The Manufacture of Gasoline and Benzene-Toluene from Petroleum and Other Hydrocarbons. By W. F. RITTMAN, C. B. DUTTON, and E. W. DEAN. U.S. Bureau of Mines, Bull. 114, Washington, 1916. Pp. 268, figs. 45, pls. 9, tables 83.

Contains the details of the methods employed by Rittman and his associates, with the results obtained on both laboratory and factory scale. The bulletin is of especial importance because it incorporates the results of experimental work that has been given wide publicity by the press.

The demand for the bulletin has been so great that the edition for free distribution was exhausted within a month of the date of its release by the Bureau.

A. D. B.

"An Arrangement of Minerals according to Their Occurrence," By E. T. WHERRY and S. T. GORDON. *Proceedings of the Academy of Natural Sciences of Philadelphia*, August, 1915, pp. 426–57.

The classification is the most comprehensive attempt that has come to the notice of the reviewer, and likewise the most successful. The divisions made are rather too numerous for use in an elementary class, but are of great value to advanced students. Doubtless other divisions could be made, which might be more useful for specific studies, such as a further division of the hydrothermal deposits for studies of ore deposits, but in general the classification is an improvement over former attempts.

A. D. B.

Corundum, Its Occurrence, Distribution, Exploitation and Uses. By A. E. BARLOW. Canada Dept. of Mines, Memoir 57. Pp. 377+vii, pls. xxviii, fig. 1, maps 2.

Corundum-bearing syenites, nephelite syenites, syenite pegmatites, and anorthosites occur in three belts north of Lake Onatario. These rocks are chiefly in the Laurentian gneiss, but are also found cutting the Grenville series. The memoir is devoted to a detailed description of the more important localities, including analyses and petrographic description of the rocks, and to the economic and technologic features of the corundum industry, not only of Canada, but of the industry in various parts of the world.

A. D. B.

Transactions of the American Institute of Mining Engineers, Vol. XLVIII. New York, 1915. Pp. 753.

This volume contains papers and discussions of the New York meeting of February, 1914. It contains papers of interest to mining men, geologists, metallurgists, oil producers, mill operators. The discussion of the general topic of revision of mining law occupies a considerable portion of the volume. More attention is given to the discussion of petroleum than in any previous volume. Of particular interest in this connection are papers by von Hofer and by Coste, presenting diametrically opposed views on the origin of petroleum. These, with the discussion they brought out, are worthy of the attention of anyone interested in the geology of petroleum deposits.

A. D. B.

Transactions of the American Institute of Mining Engineers. Vol. XLIX. New York, 1915. Pp. 853.

Contains papers and discussions of the Salt Lake City meeting of August, 1914. The greater number of papers bear on mining, milling, and metallurgy, especially on the leaching of copper ores and the methods of precipitation of copper from the solutions obtained. Forty-nine titles are included. Many of the papers are illustrated.

A. D. B.

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THE PROBLEM OF THE ANORTHOSITES

N. L. BOWEN
Geophysical Laboratory, Carnegie Institution of Washington

STATEMENT OF THE PROBLEM

Seldom can it be truly said that the puzzling feature of any object is its simplicity, yet of all the problems that the anorthosites present to us for solution the most difficult is their simple mineralogical composition. Bunsen long ago taught geologists to think of rock magmas as solutions, and the so-called solution theory[1] of magmas has now gained general acceptance. We have been enabled to understand many features of magmas that without the aid of the theory of solutions would remain incomprehensible. We understand why the order of separation of mineral from a magma is not simply the order of their fusibility. We understand also why a rock magma remains liquid at temperatures far below the temperatures of fusion of the individual minerals that enter into the magma and, therefore, why magmatic temperatures are comparatively moderate. It is because the individual minerals exist in the magma in mutual solution and therefore have their specific properties modified. But when we turn to anorthosites we find

[1] Nowadays it is scarcely proper to speak of the solution theory of magmas, for magmas are solution in virtue of the definition of a solution rather than by theory. On the other hand, to speak of the theory of solutions as applied to magmas is, of course, entirely permissible.

them made up almost exclusively of the single mineral, plagioclase. What, then, of the magmatic temperatures of anorthosites? Have we in them an exception to the rule of moderate magmatic temperatures?

Anorthosites apparently exert no exceptional influence upon surrounding rocks. Foreign inclusions, even very susceptible ones, are apparently not melted up. Inclusions of quartz-bearing rocks do not have their quartz changed to tridymite or cristobalite. Nothing in the field evidence gives us any reason to believe that anorthosites are in any way exceptional in this respect. Neither do we find any comfort in field evidence if we entertain the possibility that, in the absence of other minerals in amounts adequate to produce a great lowering of the melting temperature of plagioclase, there was present instead a sufficient amount of the much more potent "mineralizers." Typical anorthosite is notably free from all those minerals which, when present in rocks, constitute the principal evidence of the presence of volatile components in significant amounts in their magmas.[1]

An alternative possibility is that the material of anorthosites actually was in solution in something else at one time and that it differentiated from this solution. This alternative is more in harmony with general opinion, for few would state that beneath those places where we find anorthosites, there existed some anorthosite magma and that it simply was always there. It is generally believed, rather, that anorthosites are differentiates of gabbroid magma, the belief being based on field association. But it is also commonly believed that the differentiation took place in some manner in the liquid state and produced anorthosite magma. Now we must realize, and face the fact squarely, that anorthosite magma, however produced, is, nevertheless, anorthosite magma, and must exhibit the appropriate characteristics. It could separate as a liquid, by any process whatsoever, only at temperatures at which it could exist as a liquid, and we are immediately presented with precisely the same temperature problem. Anorthosites, as we have seen, do not give evidence of ever being at a temperature approaching that requisite to melt plagioclase.

[1] This matter is considered in greater detail in connection with the Morin anorthosite.

THE PROPOSED SOLUTION

For this reason in part, but also because careful consideration of all the possibilities and much experimental work to test these possibilities seem to indicate the inadequacy of any process other than crystallization, it is believed that the gabbroid magma must proceed to crystallization, and that anorthosite masses are simply collected plagioclase crystals. It is believed, then, that anorthosites were never liquid as such, but that their material when liquid was part of a solution probably of a gabbroid nature. Only in virtue of the sorting of solid, crystalline units from this solution does anorthosite come into being.

Having arrived at this belief, we may examine the anorthosites to see in how far they agree with its consequences, but before this can be done it is necessary to discuss in detail the process of sorting of crystals.

THE PROCESS OF ACCUMULATION OF CRYSTALS

General relations involved.—It must be admitted that the problem of the method of accumulation of plagioclase crystals for the formation of a mass of anorthosite is not a simple one. If the plagioclase crystals were much heavier or much lighter than gabbroic magma, all would be plain sailing. It could then be assumed that the crystals sank in the magma or floated in it, and were therefore accumulated at the bottom or at the top. But laboratory determinations of the densities of calcic plagioclase crystals and of molten gabbro place them very close together, with the crystals a very little lighter, and while the difference would not be the same and might even be in the opposite direction, there is, nevertheless, every reason to believe that it would still be small under natural conditions. As a matter of fact, we actually find this similarity of density expressed in the composition of anorthosites. If plagioclase were much lighter or much heavier, the mere accumulation of crystals would be, as we have seen, a simple matter, but the anorthosite masses formed would not be such as we find them, a fact which will become obvious from the following considerations.

During the crystallization of a magma involving the precipitation of mix-crystals the crystals first deposited are rich in the higher-

melting component of the mix-crystal series. As the magma cools, especially if it cools very slowly, these crystals continually change in composition as a result of interchange of material between liquid and crystals, the change being always in the direction of enrichment in the lower-melting component. But this change is fully accomplished only when adequate liquid is available. If the crystals are heavy and accumulate toward the bottom, the small amount of liquid there available cannot continue indefinitely to enrich the crystals in the lower-melting component. They therefore remain very rich in the higher-melting component, increasingly so the greater the preliminary accumulation of crystals. Vogt's important statistical study of the anchi-monomineralic rocks shows quite definitely that in the case of peridotites the ratio of Mg_2SiO_4 to Fe_2SiO_4 in the olivine increases directly with the proportion of olivine in the rock.[1] The orthorhombic pyroxenes apparently follow a parallel law.

This is, then, precisely as deduced above for rocks formed by the accumulation of heavy early crystals. If plagioclase were a very heavy or a very light mineral, we should find a similar relation to hold for it, namely, the greater the proportion of plagioclase in a rock, the greater would be the proportion of anorthite in the plagioclase. But when we turn to Vogt's similar study of anorthosites, we find in them a quite different tendency. The richer a rock is in plagioclase, the greater the tendency for the plagioclase to be, not a very calcic one, but the intermediate one, labradorite.[2] This character of the plagioclase is, it is believed, directly connected with the fact that the plagioclase being precipitated from gabbroic magma sensibly matches the magma in density. It is perhaps slightly lighter than the magma, but usually not sufficiently so to cause it to accumulate locally and to form masses of crystals much enriched in the higher-melting component as do olivine and pyroxene. Instead, it remains practically suspended in the liquid, with probably a very slight tendency to rise at first, and the whole of the liquid is available for the production of the change of com-

[1] J. H. L. Vogt, "Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Vid. Selsk. Skr.* I, No. 10 (1908), pp. 24–25.

[2] Vogt, *op. cit.*, p. 41.

position that ensues as the temperature falls. Thus, though the earlier crystals of plagioclase are basic bytownite, they are, in nearly all cases, gradually made over into labradorite by the liquid in which they remain suspended. In the meantime the liquid has suffered impoverishment in ferromagnesian constituents and eventually becomes decisively lighter than the plagioclase crystals. Then and then only, as a rule, does subsidence of plagioclase crystals become an important factor, and masses of anorthosite, anorthosite-gabbro, etc., are formed according to the degree of concentration of crystals. It is to be noted that this lighter liquid from which the labradorite crystals accumulate is now, of course, no longer gabbroic, but, as a result of removal of femic constituents and plagioclase, it approaches syenitic composition, and with continuation of the process actually attains the composition of syenite or granite. In the ideal case in which the process had free scope the resultant mass would be stratified, and would consist of syenite-granite, anorthosite, and pyroxenite in descending order with, in some cases, peridotites at the base. Of all these the only type that was ever liquid as such would be the syenite-granite, though liquids of every composition intermediate between that of the original gabbro and the syenite would be concerned in the process and might occur as chilled borders or in satellitic bodies. The anorthosites should be intimately related to gabbro, therefore, but as intimately related to syenite also, which might occur as interstitial material of late crystallization in some of the phases. By increase of this interstitial material gradual transition into syenite might occur.

Intimate field association of anorthosite with gabbro and with syenite is a fact that no one will question. Some have emphasized its relation to gabbro and some that to syenite, but the emphasis is due as much to the personal element and to the kind of exposures in any particular area as to any fundamental difference between the anorthosites of one area and of another. One would expect, to be sure, that the andesine-labradorite phase of an anorthosite mass would be the more intimately related to syenite, and the labradorite-bytownite phase to gabbro.

Quantitative considerations.—We can perhaps form a better idea of the quantitative relations involved in the process of collection of

crystals if we examine the crystallization of mixtures of the system —diopside, anorthite, albite—not because proportions will be the same, but because they will be rather of the same order in the natural system and will aid us in deciding whether the process is a reasonable method of producing anorthosites as we find them.

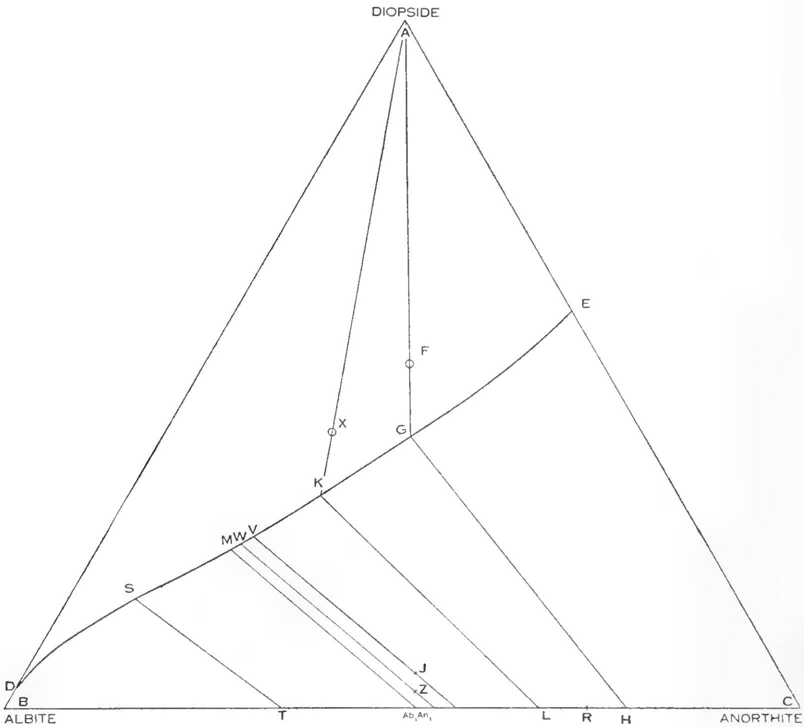


FIG. 1.—Diagram of crystallization in plagioclase-diopside melts

A liquid of composition F (Fig. 1), which contains 50 per cent diopside and 50 per cent labradorite (Ab_1An_1), begins to crystallize at 1275°, diopside separating first. As the temperature falls the composition of the liquid changes from F along AFG (directly away from diopside), and when the temperature 1235° is reached the mass consists of 17 per cent diopside crystals and 83 per cent liquid of composition G. At this temperature bytownite of composition H (approximately Ab_1An_4) begins to crystallize and the composition

of the liquid changes along the boundary curve *DE* toward *D*. Both diopside and plagioclase continue to separate, and the plagioclase crystals, not only those separating at any instant, but also those which had formerly separated, continually change in composition, becoming richer in albite. At 1220° the whole mass is made up of 37 per cent diopside crystals, 25 per cent labradorite crystals of composition *L* (Ab_1An_2), and 38 per cent liquid of composition *K*. As the temperature falls still lower the liquid gradually decreases in amount and continually changes in composition until at 1200° it is all used up, the last minute quantity having the composition *M*. In the meantime diopside and plagioclase crystals have been separating, and the plagioclase has been changing continuously in composition until at 1200°, when the last of the liquid disappears, the composition of the feldspar is Ab_1An_1. The whole mass now consists of 50 per cent diopside and 50 per cent Ab_1An_1.

Crystallization takes place according to the foregoing outline if no sinking of crystals occurs. If diopside crystals sink, no effect on the composition of the liquid results. We should have then at 1220° a mass in which the diopside crystals were of increasing concentration toward the bottom, and in which a certain upper portion was free from diopside crystals, consisting of 60 per cent of liquid of composition *K* and 40 per cent labradorite crystals of composition *L* (Ab_1An_2). Let us imagine that at this stage appreciable sinking of plagioclase crystals begins, and that it increases in importance as the liquid changes toward *M*, and therefore becomes lighter. It is necessary to imagine also that the plagioclase crystals sink very slowly, and are outstripped by the heavy diopside crystals which are forming simultaneously and which increase in size more rapidly since the liquid is becoming relatively impoverished in diopside. It seems possible, then, that, locally at least, plagioclase crystals might accumulate in a mass free from diopside crystals and containing only a little interstitial liquid whose composition would lie between *K* and *M*. If the mass had 20 per cent interstitial liquid of composition *V* and 80 per cent crystals slightly more calcic than Ab_1An_1, the final rock formed on solidification of the interstitial liquid would consist of 95 per cent Ab_1An_1 and 5 per cent

diopside (J). If the mass had only 10 per cent interstitial liquid of composition W and 90 per cent crystals slightly more calcic than Ab_1An_1, the final rock would consist of 98 per cent Ab_1An_1 and 2 per cent diopside (Z). This degree of concentration of plagioclase is ample for the production of nearly all anorthosites, and is more than sufficient for most of them. To understand the formation of anorthosites of extreme purity it is necessary to follow what has been happening to the liquid in the meantime, that is, to that part of the liquid from which crystals have subsided. Instead of becoming completely crystalline when the composition M is attained, it continues to change its composition toward S and may go even beyond S, that is, it becomes very rich in albite (haplo-syenitic)[1] and the diopside becomes a vanishing quantity. Now it can be considered that locally the interstitial liquid occurring between the plagioclase crystals was of this type, which it might be if the rate of interchange of material did not quite keep up to equilibrium requirements, a very likely possibility. On complete solidification of such a mass anorthosite of extreme purity would result. This would be more likely to give a rock made up of acid labradorite or even of andesine-labradorite. It is because plagioclase crystals may accumulate, under certain circumstances, in a liquid which is itself nearly pure plagioclase (though very different from the crystals in composition) that we can get plagioclase rocks of such extreme purity.[2] For the case of natural rocks the interstitial liquid is enriched, not merely in albite, but also in orthoclase and to some extent in quartz. In those anorthosites that run very low in bisilicates we therefore commonly find 5 per cent or more orthoclase, and occasionally some quartz.

In the foregoing the writer has done his best to picture a process whereby plagioclase crystals may accumulate in sufficient force to give a mass of anorthosite. Unquestionably there are some difficulties, the gravest being that connected with the nearly complete sorting of plagioclase and pyroxene, whose periods of crystal-

[1] N. L. Bowen, "The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Am. Jour. Sci.* (4), XL (1915), 161.

[2] Another possible method of obtaining extreme monomineralic composition is suggested later (p. 238).

lization are in large part contemporaneous. If one could assume that plagioclase follows pyroxene in the crystallization of gabbro, as some geologists appear to do, the sorting would be a simple matter, but chemical considerations will not permit such an assumption. Yet the difficulties do not seem insurmountable, especially in comparison with those connected with other processes. Diffusion is hopelessly incompetent even if it is assumed that its tendency is in the proper direction. Liquid immiscibility, whose operation in the case of silicates has nothing to support it, would certainly not tend to produce pure liquids in any case, but only to produce liquids of contrasted composition, all being, nevertheless, mutual solutions of minerals. Added to these is the temperature objection to which reference was made on an earlier page, and still others might be mentioned. On the other hand, it does seem reasonably probable that a mass of gabbroid magma might cool sufficiently slowly to permit the necessary amount of sorting of crystals especially if it was a large mass, or if it was very deeply buried.

CHARACTERISTICS OF ANORTHOSITE CONSEQUENT UPON THE SUPPOSED METHOD OF FORMATION

It must be admitted, however, that opinion as to whether the process can take place is not a very decisive matter. More important is the deduction of its consequences followed by a survey of the characteristics of anorthosites in order to determine to what extent they agree with the requirements. If anorthosites are generated only by the accumulation of crystals, then the more nearly a rock mass approaches an exclusively plagioclase composition, the more nearly it should have approached the completely solid condition when that composition was attained. In discussing artificial melts we have seen that if we have a portion with 80 per cent plagioclase crystals and 20 per cent interstitial liquid it would, on crystallization, have 95 per cent plagioclase and 5 per cent diopside. In other words, a rock containing only 5 per cent diopside could have had, after that total composition had been attained by the process we are considering, not more than 20 per cent liquid. A rock containing 10 per cent diopside could have had a maximum of 35 per cent liquid, and one containing only 2 per cent diopside

could have had not more than 10 per cent liquid. For natural melts the figures would not be the same, and the probability is that the amount of liquid would be relatively somewhat larger on account of the presence of orthoclase in the liquid. Assuming the figures to be approximately the same, it seems necessary to believe that a rock containing 95 per cent or more plagioclase, if it is true that it is formed by the method outlined, should exhibit certain characteristics that set it apart from such a rock as a granite, which, as we know well enough, often occurs in the completely molten condition. When the plagioclase rock is formed *in situ*, it need exhibit no features differentiating it from other igneous rocks except perhaps a marked coarseness of grain. Such a body, while still containing nearly its maximum of about 20 per cent interstitial liquid, might be moved *en masse*, though probably not far, from the position of its original formation, but this movement would be accompanied by the development of protoclastic structure, especially about the margins. Since all crystalline igneous rocks pass through a stage at which they are 80 per cent crystalline, all are subject to the possibility of the development of similar structures under parallel conditions. The plagioclase rock differs only in that it cannot be moved without developing this structure, since if moved when containing more than 20 per cent liquid the mass moved has not yet attained the requisite degree of concentration of plagioclase crystals. Protoclastic structure and granulation should therefore be perfectly general features of all moved anorthosite masses and very common features of all anorthosites.

When we come down to the movement of such material in small masses, it seems impossible that it would be capable of being injected into small openings in cold country rock—in other words, that it would form no small dikes in such rocks, though it might occur as dikelike masses in consanguineous igneous types, being injected into them at a time when they themselves were not completely crystalline. Such material should, moreover, be incapable of occurring as effusive flows.

For the purposes of the foregoing discussion a mass containing 20 per cent interstitial liquid has been arbitrarily chosen. It is a matter of opinion how much liquid a mass must have in order to

be injected as small dikes. If it is considered that about 50 per cent liquid is necessary, then only anorthosite or, better, anorthosite-gabbro, with about 85 per cent plagioclase could occur as small dikes. If somewhat less than 50 per cent liquid is necessary, then a rock somewhat richer in plagioclase could occur in that manner. In the case of effusive masses, if it is considered that more than 50 per cent liquid is normally requisite for their formation, only anorthosites with less than 85 per cent plagioclase could occur as effusives.

A study of the literature of anorthosites from various localities seems to show that, in so far as published descriptions are concerned, anorthosites do have substantially the characters outlined in the foregoing discussion, which is based on the hypothesis that they are accumulated masses of plagioclase crystals. Still the idea is rather novel, and probably no one had such a hypothesis in mind when examining anorthosites, so that, while many observations bearing directly on the problem are recorded, one might readily believe that perhaps many others equally pertinent escaped record. For this reason the writer spent a few weeks in the Adirondack area and in the Morin area of anorthosites, becoming acquainted at first hand with the relations there found. Attention was confined almost entirely to parts already mapped in detail so that a maximum could be seen in the limited time. The facts bearing on the origin of anorthosites in these areas will be stated principally as recorded by others, and only to a very limited extent supplemented by this brief personal experience. It is desired to express thanks to Professors Kemp, Cushing, and Adams and to Mr. Dresser for interest taken and for furtherance of the work in various ways.

THE ADIRONDACK ANORTHOSITE

General relations.—The anorthosite of the Adirondacks occurs principally as a single great area, for the most part in the heart of the mountains and making up its highest peaks, though extending eastward to the lower country in the vicinity of Lake Champlain. The mass occupies an area approximating 1,200 square miles, the principal constituent of the rock throughout this area being plagioclase. Large exposures may be made up almost exclusively

of plagioclase, while other exposures, perhaps equally general and widespread, would average nearly 10 per cent bisilicates. This latter type seems to prevail even in the heart of the area being represented in most of the exposures of the Keene Valley, while the bare ledges of the summit of Mt. Marcy average probably more than 5 per cent bisilicates. Toward its borders, too, the anorthosite commonly passes into anorthosite-gabbro and gabbro. Nevertheless, the mass as a whole is aptly described as consisting of "little else than feldspar which is generally a blue labradorite."[1] If this great mass, whose volume is to be measured in thousands of cubic miles, was ever molten as such, it is remarkable that none of the many investigators who have studied the area have found a single dike consisting of nearly pure plagioclase in the surrounding rocks. The evidence of the intrusive nature of anorthosite in its more typical development depends on the occurrence of Grenville inclusions in it. To be sure, the anorthosite is nearly always immediately surrounded by a younger rock, the syenite, but in several localities the invading power of certain phases of the anorthosite mass is well shown. Anorthosite-gabbro invades the Grenville and associated older gneisses in places, and occurs as outlying masses upward of 20 miles distant from the main anorthosite mass. As soon, then, as the bisilicates mount to 20 or 25 per cent there is no lack of evidence of the power of the mixture to penetrate into openings in the surrounding rocks. The great mass of the anorthosite itself contains much fewer bisilicates, yet in spite of the overwhelming volume of such material it is entirely unrepresented as dikes and small intrusions. It seems to be a reasonable conclusion that this material was incapable of being injected into the older rocks.

Intimate relation of syenite and anorthosite.—The anorthosite core of the Adirondack igneous mass is surrounded practically everywhere by the syenite-granite series with which are associated numerous areas of Grenville sediments and perhaps older granite gneiss. There has been a considerable tendency to consider the syenite-granite as an igneous unit and anorthosite as a separate unit. This tendency has been emphasized perhaps by the fact

[1] D. H. Newland, *N.Y. State Museum Bull. 119*, 1908, p. 17.

that in one locality, in the vicinity of Long Lake, Cushing was able to demonstrate that the syenite is younger than the anorthosite. Yet even Cushing states: "The syenite and anorthosite seem surely derivatives from the same parent magma and of no great difference in age."[1] This aspect of the anorthosite, i.e., its intimate connection with the syenite, is emphasized in the area as a whole, where, in spite of fairly good exposures, only one other locality showing the intrusive relation of syenite to anorthosite has been found, but where, on the other hand, types intermediate between the two are rather commonly found. This feature of Adirondack igneous geology has not been studied in detail except, apparently, at the one locality in the Long Lake quadrangle, though it appears to deserve such study since it marks the great similarity between the Adirondack anorthosites and others, the Norwegian and Volhynian occurrences, for example. In the writer's limited experience it was found that the change from anorthosite to syenite was heralded by the appearance of inclusions of potash feldspar in the plagioclase. The inclusions are small patches, uniformly oriented and constituting therefore an antiperthite.[2] These inclusions often show a rather peculiar feature which, so far as the writer is aware, has not been noted elsewhere. Surrounding some of them and corresponding in general though not in detail with the outline of the inclusion is an area of plagioclase differing from the crystal as a whole. Its outline is usually sufficiently sharp to make it possible to determine that it has a slightly higher refractive index than the rest of the plagioclase, besides a different position of extinction which makes it a rather conspicuous feature. An extremely fine twinning, not shown by the main body of the plagioclase crystal, can usually be seen with high magnification. A suggested explanation of these features is that the material of the microcline inclusions was originally in solid solution in the plagioclase and that on separating from solid solution it left the plagioclase poorer in potash feldspar, and therefore of higher refraction than the general body of the crystal more remote from the inclusions. But the rims about the inclusions usually have not much greater mass than the inclusions

[1] *Bull. Geol. Soc. Am.*, XVIII (1907), 485.

[2] F. E. Suess, *Jahrb. K. K. geol. Reichsanst.*, LIV (1904), 417–30.

themselves, and it would be necessary for the surrounding plagioclase to have contained originally nearly one-half potash feldspar, which it certainly did not. It seems more likely that the potash feldspar, though occurring as definite inclusions, was, nevertheless, formed from the portion which remained liquid last and was introduced into the plagioclase by a sort of replacement, the change in the plagioclase aureole being an effect going hand in hand with this replacement.

With the microcline inclusions some interstitial microcline generally makes its appearance, and this may increase in amount until it becomes an important constituent of the rock. In such a specimen the plagioclase is usually andesine rather than labradorite, though the large blue labradorites typical of the anorthosites often occur as phenocryst-like individuals. The rock is definitely intermediate between anorthosite and syenite, though the microcline, in the few slides examined, has not as marked a tendency to be perthitic as it has in the typical syenite. One sees these intermediate types in some of the exposures about the shores of Lake Placid. There is apparently a transition between some of the rocks mapped as gneiss (syenite-granite) and those mapped as anorthosite in that vicinity.[1] Similar intermediate types are found in the vicinity of Elizabethtown, and as a whole they seem to be closely analogous to the perthitophyres of Volhynia as described by Chrustschoff,[2] and to the Norwegian monzonites described by Kolderup.[3]

An interpretation of the structural relations of syenite and anorthosite.—While the anorthosite and syenite are evidently closely related and connected by transitional types, they are usually very distinctive. There is one aspect of their field relations in which they are strongly contrasted and with which the writer was impressed in the field. In the great area of syenite-granite that surrounds the anorthosite core, areas of Grenville are exceedingly numerous. In many of the mapped quadrangles it has been neces-

[1] Map accompanying report by Kemp, "Geology of the Lake Placid Region," *N.Y. State Museum Bull. 21*, 1898. Since the above was written the writer has been informed by Professor William J. Miller that, while the transitional relation is shown, the syenite also sends dikes into the anorthosite.

[2] *Tschermak's Min. Petr. Mitt.*, 9 (1888), p. 470.

[3] *Bergens Museums Aarbog*, No. V (1896), p. 86.

sary to use a color to represent a mixture of Grenville and syenite that defies separate mapping. Now the manner of occurrence of the Grenville when found in considerable areas is commonly as a roof lapping over the syenite and showing only comparatively moderate dips. One sees this in typical form on the shores of Lake Champlain immediately north of Port Henry, and Miller has recently described this relation in widely scattered Adirondack localities, the large-scale example in the Blue Mountain quadrangle being of special interest.[1] Syenite and Grenville in this relation are almost constant companions.

The anorthosite areas, on the other hand, are very different. It could be said with little exaggeration that on passing the borders of the anorthosite core one encounters only anorthosite. It is true that inclusions of Grenville have been found, enough to prove the intrusive nature of the anorthosite, but these appear to be small completely inclosed blocks and do not suggest actual roof remnants. In spite of their occasional occurrence the contrast between the syenite and anorthosite areas is very striking. One has but to glance at the maps of such areas as the Paradox Lake and Long Lake quadrangles to be convinced of it. Not only is the anorthosite unbroken by areas of Grenville, especially away from the margins, but it is likewise practically free from protrusions of the syenite, although the syenite is, as we have seen, in part at least, a later rock. If one pictures the syenite and the anorthosite as conventional batholiths, some difficulty is experienced in accounting for the foregoing facts. It is necessary to imagine an early intrusion of a huge plug of anorthosite followed by an intrusion of syenite which took the form of a hollow cylinder circumscribing it and invading it only peripherally. All of this must take place without throwing the Grenville series into appressed folds, indeed, without very significant folding of any kind. It is then necessary to imagine that erosion removed every vestige of a roof from the small interior anorthosite area, and left great stretches of it throughout the broad syenite-granite belt that surrounds it.

All of this is perhaps possible, but at the same time seems highly improbable. On the other hand, if one pictures the Adirondack

[1] William J. Miller, *Jour. Geol.*, XXIV (1916), 591.

complex as essentially a sheetlike mass with syenite overlying anorthosite, the facts of Adirondack igneous geology seem to arrange themselves more rationally. On this supposition one would expect to find areas of the Grenville roof covering the syenite in places and to find it relatively little disturbed. In the interior and

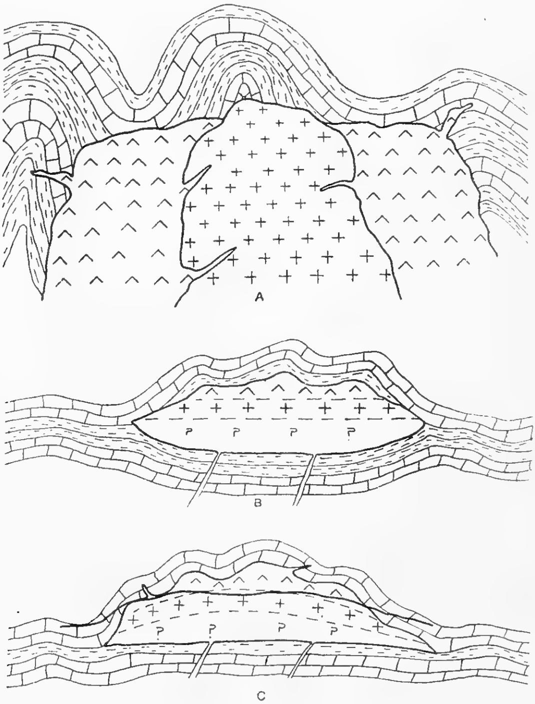


FIG. 2.—A. Adirondack complex interpreted as batholitic. +Anorthosite, ^ Syenite
B. Adirondack complex interpreted as laccolithic (undisturbed)
C. Same as B after disturbance. Heavy line indicates erosion surface

eastern region of maximum uplift one would expect to find the deeper-seated anorthosite laid bare and to find it free from areas of the roof since it was for the most part separated from the roof by a layer of syenite. (In Fig. 2 the alternative interpretations of the Adirondack complex are presented.)

On this supposition of the origin of syenite and anorthosite by gravitative differentiation of a sheetlike mass it is by no means

necessary that syenite and anorthosite should always grade imperceptibly the one into the other. The Adirondack area is one of considerable disturbance. It no doubt suffered some disturbance at the time of the intrusion of these igneous masses, and it has unquestionably been much faulted since their consolidation. Is it reasonable to suppose that the region necessarily stood stock-still during the long period required for the consolidation of these igneous masses? It is, in fact, likely that faulting took place during this period as well, and if it occurred at a time when the anorthosite was completely crystallized but the syenite still molten then it is quite possible that syenite might thus be brought laterally against, and acquire an intrusive relation to, anorthosite. The fact that syenite invades anorthosite locally need not therefore be fatal to the conception of gravitative differentiation of these two types, nor does it necessarily indicate the order of their arrival from the depths. A diagrammatic simplicity is not to be expected, but the broader relations, including the substantial freedom of the whole interior of the anorthosite area from protrusions of syenite, seem to give a distinct preference to their arrangement substantially as layers with the syenite above as outlined in the foregoing.[1]

The writer's leaning toward differentiation practically in place as the explanation of the variation of many batholiths has been criticized publicly by Harker,[2] and by others in private correspondence. It is apparently believed that when one rock invades another the relation necessarily means that the invading rock arrived from a deep-seated magma basin subsequent to the other. This may be quite true, as a rule, but there is little evidence in most cases that adequate consideration has been given to the alternative view of differentiation practically in place with only relatively minor disturbance during the magmatic period. The petrologist should be reluctant to reject this possibility without fair trial, for he destroys some of the hope of solving the problems of igneous

[1] A few small patches of syenite have been found within the anorthosite area. If these are regarded as having been pushed up from below as pipes, it is rather remarkable that in no instance has their intrusive nature been demonstrated. On the other hand, if they are remnants of an overlying syenite, they might well lack a definite intrusive character.

[2] *Jour. Geol.*, XXIV (1916), 554.

geology by thrusting the locus of differentiation ever backward into unseen depths. The Adirondack intrusives would, it is felt, be interpreted by many in the conventional manner, and for this reason some pains have been taken to present the alternative view.

Daly regards the Adirondack anorthosite-syenite complex as probably a laccolith. According to his views anorthosites are formed in laccoliths because those masses suffer little contamination from wall-rock material and anorthosite is a pure differentiate of gabbro magma. A certain amount of assimilation of wall rock can occur, however, without eliminating the possibility of the formation of anorthosite, and under such circumstances the syntectic magma differentiates in such a manner that syenite is formed. In batholiths, on the contrary, whose emplacement takes place by stoping, the consequent assimilation has so important an effect on the gabbroic magma that no anorthosite is formed, according to Daly. The writer's interpretation of the Adirondack complex as a stratified, sheetlike mass with a lower layer of anorthosite and an upper layer of syenite intimately associated with the Grenville sediments is therefore in striking agreement with Daly's conception. However, a consideration of crystallizing magmas in the light of experimental study compels the writer to believe that there would exist in association with the anorthosite a mass of syenite, even if the invaded rocks were of infinitely refractory and inert materials. The mass of syenite was probably augmented by assimilation of foreign rocks, but that is a different matter. Apparently this opinion is in accord with the conclusions of those best acquainted with the Adirondack rocks in the field who, while demonstrating that assimilation takes place, consider it rather as an incident than as a fundamental factor controlling the genesis of rock types. And, again, the writer's interpretation of the igneous mass as sheetlike is offered merely because of the difficulty of picturing the general relations otherwise. Indeed, it is not considered that the Adirondack batholith or laccolith or whatever it may be called, is exceptional in this respect. Most batholiths are regarded by the writer as just such masses. Consequently it is believed that the shape of the intrusive is not the determining factor in the formation of

anorthosite. It is rather a balance between density, rate of cooling, and viscosity such that the necessary amount of sorting of crystals occurs.

The writer must confess an inability to state precisely the reason why the species presented in an igneous sequence at one locality may be different from those at another. It is nevertheless believed that it is unnecessary that the original magmas need have been different, or even that the manner of differentiation need have varied. The results seem to be possible if there was a variation in the extent to which separation of crystals from liquid and also sorting of individual minerals were able to take place. Variations in these factors depend on physical conditions which have, however, their chemical consequences, for the removal or non-removal of a crystal has each a perfectly definite effect on the future course of the liquid.

In one sequence, which is well shown in the pre-Cambrian of Ontario and in certain British intrusives, there is practically only gabbro and granite with little that could be described as intermediate. Apparently this is especially likely to be true of masses of moderate size. In somewhat larger masses ultrabasic rock may make its appearance as one of the members with occasionally some anorthosite. Usually for the formation of anorthosite a very large mass is necessary, and possibly also a deep-seated mass. On the other hand, for the formation of those sequences that emphasize intermediate types such as diorite, quartz diorite, and granodiorite the indications are that very large masses are necessary, but that they should probably occur at moderate depths. There is nothing here in the way of hard and fast rules, but there do seem to be fairly definite tendencies. All of these are reasonably to be considered the result of differences of the physical conditions under which cooling took place.

THE MORIN ANORTHOSITE

General features.—The Morin anorthosite area of Canada is in many respects very like the Adirondack arêa. It lies near the edge of the great pre-Cambrian shield where it is overlapped by Paleozoic rocks. It covers a territory of about 1,000 square miles which, while not as mountainous as the Adirondacks, is nevertheless quite

rugged, many of the important elevations of the Laurentian Mountains of that region lying within the boundaries of the anorthosite mass. As with the Adirondack Mountains, the Laurentian Mountains have suffered glaciation and lakes abound, with the result that even in the matter of popularity as a summer resort the two regions are alike, the Laurentian region drawing a plentiful supply of tourists on account of its proximity to the Canadian metropolis. Coming to the more fundamental matters of geologic structure and petrography we find again a remarkable degree of similarity to which attention is directed in the sequel.

An area of more than 3,000 square miles comprising the Morin anorthosite was mapped nearly thirty years ago by F. D. Adams, and a map published on a scale of four miles to one inch.[1] The map is therefore not as detailed and does not form as useful a guide for one who would see a great deal in limited time as do the quadrangle maps of the New York State Museum, which are the result of the labors of a number of workers. On the other hand, the text of the report is full of minute descriptions of localities, and a brief visit was paid to some of these in order to become familiar with them at first hand.

Relation of anorthosite to the surrounding rocks.—The Morin anorthosite occurs, as does that in the Adirondacks, principally as a single, great intrusive mass. There is, however, a greater number of small outlying masses that give the area a somewhat greater interest with reference to the problem of the origin of anorthosite. The associated rocks are practically identical with those in the Adirondacks, consisting of igneous gneisses largely of salic composition and of sediments of the Grenville series. Of all these Adams concluded that the anorthosite was the youngest, a relation which he appears to have considered a general one for the Canadian anorthosites including the great Saguenay mass. Recent study of the Saguenay area has shown, however, that there are associated with the anorthosite certain more salic types, possibly consanguineous with it, but of somewhat later age,[2] the whole being appar-

[1] "Geology of a Portion of the Laurentian Area North of the Island of Montreal," *Geol. Surv. Can. Ann. Rept.*, Vol. VII, Part J, 1896.

[2] Personal communication from Mr. Dresser.

ently a counterpart of the anorthosite-syenite association in the Adirondacks.

While the writer has nothing very definite to offer concerning a similar association in the Morin area, certain indications were found tending to show that detailed study might definitely bring out its existence there. In the vicinity of Piedmont and extending southeastward beyond Shawbridge the gneiss which here forms the southern boundary of the anorthosite mass is a rather fine-grained greenish rock looking very similar to the syenite of the Adirondacks. Specimens of this taken at various distances from the borders of the anorthosite show that it varies considerably. In all cases the rock is composed principally of plagioclase but, on receding from the border of the anorthosite, orthoclase continually increases in importance. There is apparently a perfect transition from anorthosite toward syenite, though in none of the specimens collected had the change gone to completion, that is, none of the specimens could be called typical syenite. In one specimen, however, orthoclase made up about 30 per cent of the rock, and was accompanied by some quartz, so that probably the change would not have to be followed much farther to afford typical syenite.[1] On account of this transitional relation it is very difficult, at least where seen by the writer, to fix a boundary between anorthosite and gneiss. Specimens that are apparently typical anorthosite and taken well within the boundary of the mass as mapped by Adams, are found to be like those types of anorthosite of the Adirondacks which show the beginning of transition to syenite in that the plagioclase contains orthoclase inclusions. Specimens from the cliffs north of Piedmont station show the orthoclase in streaks forming an antiperthite much richer in orthoclase than any seen in Adirondack specimens.[2] Even specimens taken four miles within the border of the anorthosite, in the village of Ste. Adèle, show abundant orthoclase inclusions in the plagioclase.

[1] Professor Adams informed the writer in conversation that intermediate monzonite types analogous to the Norwegian types of Kolderup occur in the region, so that, while they are not described at length in his report, he undoubtedly recognized such types.

[2] In none of the Canadian specimens was there seen any peculiar zone of plagioclase surrounding the orthoclase inclusions as described from the Adirondack localities.

In the vicinity of Piedmont occasional dikelets are seen cutting the anorthosite, which are found to consist principally of microperthite with some quartz and an unusually large amount of magnetite, a composition that suggests a syenitic source. Taken all in all the evidence favors the possibility that we have in the Morin area syenite and anorthosite related in the same manner as in the Adirondacks, in part transitional into each other, but the syenite of somewhat later consolidation. Even in the matter of the occurrence of a certain aberrant type the two regions show a further similarity. In the vicinity of Elizabethtown, New York, there is a peculiar dark rock resembling a basic syenite, but containing phenocrysts of the blue labradorite which is described by Kemp as the Woolen Mill type.[1] This rock is duplicated in both megascopic appearance and microscopic characters in exposures in the streets of the village of St. Jérome, Quebec. It is apparently intimately related to both syenite and anorthosite.

Concerning the structural relations of syenite-granite and anorthosite it is impossible to say anything definite, since syenite that may be regarded as probably related to the anorthosite has not been delimited. About twenty miles east of the anorthosite mass, syenite-granite makes its appearance from beneath the flat-lying gneiss of the surrounding country. Adams considers that the syenite is much more widespread, the gneiss of the surrounding area forming merely a relatively thin and little disturbed roof over it. If the anorthosite is, as in the Adirondacks, a deep-seated portion of the same igneous complex, then in order to bring the anorthosite and the roof gneiss into lateral juxtaposition a considerable movement would be necessary, and it is found that, after passing westward over a twenty-mile stretch of little disturbance, the gneiss is then, on approaching the anorthosite, thrown into sharp folds.[2] Moreover, we find on passing within the border of the anorthosite mass that the typical roof gneiss with its occasional bands of limestone is absolutely lacking, a fact that suggests that the roof gneiss was nowhere superposed directly upon the anortho-

[1] "Geology of the Elizabethtown and Port Henry Quadrangles," *N.Y. State Museum Bull. 138,* 1910, p. 35.

[2] Adams, *op. cit.*, pp. 11 and 12.

site. Not impossibly, then, there may be in the Morin area a stratified mass, made up of syenite above and anorthosite below, with general relations similar to those we have imagined to exist in the Adirondacks.

Lack of mineralizers in the Morin anorthosite.—On an earlier page it was pointed out that there is in anorthosite no supply of minerals other than plagioclase adequate to produce significant lowering of the melting temperature of the plagioclase. Anorthosite could exist as magma, therefore, only at very high temperatures unless there was present a proportion of volatile components sufficient to produce great lowering. Adam's work on the Morin anorthosite appears to give a definite negative answer to this possibility. The minerals normal to the anorthosite are those commonly believed to form from relatively anhydrous melts. The ferromagnesian material appears typically as pyroxene, not as hornblende or mica. There is little if any tendency for the pyroxene to be made over into hornblende or mica even in the very latest stages of crystallization when the volatile components would reach their maximum concentration. Even intense shearing of the rock, which took place partly during this latest stage of crystallization and partly immediately subsequent thereto, had no tendency to develop hornblende and mica from the pyroxene, though under such conditions it is well known to be particularly susceptible to this change if there are mineralizers present in significant quantity.

All of the evidence points to a substantial lack of mineralizers. The Morin anorthosite is in these, as in most respects, typical of the world's anorthosites. We are therefore impelled toward the belief that, inasmuch as anorthosites show no definite high-temperature characters, they are preferably to be considered as never having been molten as such.

Anorthosites as small intrusions.—In considering the physical condition of the anorthosite as bearing on this question of its origin it is perhaps well to recall the circumstances under which Adams' investigation was undertaken. Prior thereto there had been a common tendency to believe that all banded rocks were of sedimentary origin, and since the anorthosite is often markedly banded it had been regarded as a member of the sedimentary series with

which it is associated. Adams entered the field as the champion of the newer conception that many banded gneisses are of igneous origin, and that of these the anorthosite was a prominent representative. Under such circumstances it cannot be questioned that any geologist would search diligently for dikes and tongues of anorthosite running out into the surrounding rocks, and that having found them he would not fail to record them. Yet one will search Adams' report in vain for a single instance of such a dike. The wording of the one statement which is an apparent exception serves only to emphasize the truth of the above. The anorthosite mass is described as "sending *an apophysis*" into the surrounding gneiss.[1] The apophysis referred to is a great armlike extension five miles wide. Attention is directed to this lack of dikes in order to emphasize that here we have an intrusive of a peculiar character, not to call in question the interpretation of the anorthosite as an intrusive. Of that there can be no question. Dikes intimately related to the anorthosite do occur, but they serve to emphasize the more that there are none consisting almost entirely of plagioclase, though there is mile upon mile of such rock within the main body of anorthosite. It seems reasonable to conclude, therefore, from the evidence in the Morin area, that a rock consisting almost entirely of plagioclase is incapable of being injected as dikes. The reason for this is to be found, it is believed, in the manner of its origin, a mass of anorthosite being merely a collected mass of plagioclase crystals.

There are, as has been stated, several small outlying masses of anorthosite besides the great central mass. These are listed and described in detail by Adams. Some of them were visited by the writer, but nothing need be added, indeed nothing can be added, to Adams' statements, which are quite explicit with reference to the point that it is desired to emphasize. In discussing the anorthosite of the outlying masses in general he states: "It is perhaps on the whole richer in iron magnesia constituents and often contains minerals such as hornblende and biotite."[2] Statements of like import are made in discussing the bands severally. Of the Kildare

[1] *Op. cit.*, p. 116. Italics are the writer's. [2] *Ibid.*, p. 117.

bands he says: "The rock is on the whole richer in bisilicates than the Morin anorthosite, approaching more nearly a normal gabbro or norite in composition."[1] Practically the same statement is made of the Cathcart bands;[2] and again of the Brandon bands he says: "Like most of the small anorthosite bands described in this report, these from the township of Brandon are usually richer in bisilicates than a true anorthosite should be."[3]

Apparently, then, these outlying bands always vary from typical anorthosite, usually toward gabbro, but in one or two instances perhaps the variation is toward syenite-granite, as suggested by a content of hornblende and biotite. The bands are by no means inconsiderable bodies, usually having a width of upward of half a mile or more and a length of several miles. Even masses of this size are apparently never made up of nearly pure plagioclase rock, a fact that accords with the belief that a fair proportion of other minerals is necessary before anorthosite acquires appreciable invading power in masses of limited size.[4]

CONSIDERATION OF ANORTHOSITES IN GENERAL

The agreement of the two most completely described areas of anorthosite on the North American continent with the consequences of the hypothesis of the origin of anorthosite is apparently rather good. The Norwegian and the Russian areas are equally significant, but no attempt will be made to discuss them in detail. Reference will be made, however, to the schematic presentation of differentiation given by Kolderup, which is based entirely on field evidence, and of which a copy is presented below. Attention is called to the central position of the norite with its anchimonomineralic basic differentiates and its more complex acid derivatives. These are, it is believed, the accumulations of sorted crystals on the one hand, and the residual liquids on the other.

[1] *Ibid.*, p. 122. [2] *Ibid.*, p. 124. [3] *Ibid.*, p. 126.

[4] A dike of anorthosite in the Cripple Creek country, to which the writer's attention was called by Professor Graton as an apparent exception, is described as containing biotite and quartz. It evidently varies toward granite, and its occurrence as a dike might reasonably be expected.

KOLDERUP'S REPRESENTATION OF DIFFERENTIATION IN THE EKERSUND-SOGNDAL ANORTHOSITE AREA

Bronzite granite
|
Adamellite
|
Banatite
|
Monzonite
|
Quartz-norite
|
Gabbro-norite—Norite—Anorthosite-norite—Anorthosite
|
Bronzitite—Norite-bronzitite
|
Ilmenite-norite
|
Ilmenitite

Kolderup's anorthosites become more basic and schistose toward their borders and their contact relations are obscure. One cannot be sure from his text whether there are small dikes of anorthosite in the surrounding rocks or not, but apparently there are not.[1]

Apophyses consisting of 95 per cent basic labradorite and 5 per cent augite cut the Sooke gabbro of Vancouver Island described by Clapp.[2] The anorthosite veins and the gabbro are consanguineous, however, and the former with, say, 20 per cent liquid might have been squeezed into the not completely crystallized gabbro mass, the process involved being then rather different from that occurring in the injection of anorthosite into cold country rock.

Dikes of anorthosite are described as cutting the older rocks in the Rainy Lake region, but one cannot be sure from the description whether the dikes are strictly anorthosite or rather the related anorthosite-gabbro.[3] And so it is with many descriptions. It is profitless, therefore, to pursue the discussion of various anorthosite occurrences further since they were not examined with the questions

[1] "Die Labradorfelse des westlichen Norwegens," *Bergens Museums Aarbog*, No.V (1896), p. 14.

[2] C. H. Clapp, "Southern Vancouver Island," *Geol. Survey Canada Mem. No. 13*, 1912, p. 116.

[3] Since the above was written Professor Coleman has informed me that in so far as he can recall there are no dikes of typical anorthosite.

raised in mind. An individual cannot do more than state the problem and leave its suggested solution to confirmation or refutation at the hands of those acquainted with various anorthosites in the field.

Of anorthosite in general it can be said, however, that no effusive equivalent has hitherto been found anywhere. This must be regarded as a very surprising fact if there were ever masses of molten plagioclase adequate to furnish such great exposures of anorthosite as occur in various parts of the earth. On the other hand, if these anorthosite masses were merely collections of plagioclase crystals effusive anorthosites are scarcely to be regarded as possible.

MONOMINERALIC ROCKS IN GENERAL

Enough has been said incidentally in the foregoing to make it clear that the problem of any monomineralic rock is, in its essentials, the same as the problem of the anorthosites. There are no more promising methods of obtaining pure molten olivine or pyroxene than there are of obtaining molten plagioclase. On the other hand, the collection of crystals to give substantially solid masses of nearly pure olivine or pyroxene does not seem out of the question.

A survey of the domain of igneous geology lends considerable support to the possibility that peridotites and pyroxenites are so generated. In making the test of their occurrence as small dikes we find that this is perhaps the most characteristic manner of occurrence of peridotite, but on closer examination it appears that this fact may be due rather to the elastic nature of the term peridotite, which may be applied to a rock containing considerable plagioclase, pyroxene, hornblende, or mica, or all of these, as well as its olivine. Typical dunite, or nearly pure olivine rock, however, probably does not occur as dikes, if we except, again, its occurrence in such form in closely related and essentially contemporaneous igneous rocks. The same statement may be made of rock types excessively rich in pyroxene. As to the question of their occurrence as effusive types it is found that peridotite has an effusive equivalent in picrite, but picrite is far from being a pure olivine rock. Dunite itself has apparently no effusive equivalent. With the

pyroxenites the case is apparently the same. Limburgite and augitite can scarcely be regarded as monomineralic rocks in the stricter sense of the term, and that is the only sense in which it can be used in testing the hypothesis. The presence of both pyroxene and olivine, of a glassy base and usually of some feldspathoid makes it clear that these effusive pyroxenites do not constitute an exception to the rule that the monomineralic rocks do not have effusive equivalents. Apparently, the facts are in accord, therefore, with the hypothesis that monomineralic rocks are accumulated masses of crystals.[1] Mention may be made again here of Vogt's discovery that the richer a peridotite is in olivine, the richer the olivine is in magnesia, a fact which is readily explained on the assumption that peridotites are made up of accumulated early crystals.

All of the monomineralic rocks often do occur, however, in a manner which has led a very great number of investigators to speak of the magmas of these rocks as freely as of the magmas of any others. This is probably due partly to the fact that the possibility of their origin after the manner here advanced did not occur to the investigators, but whether this was always the case is a question that, again, an individual cannot answer. One of the most remarkable occurrences of anchi-monomineralic rocks, especially pertinent in the present connection, is that described by Harker from the islands west of Scotland. As a result of his minute descriptions an especially favorable opportunity is offered of discussing these rocks in the light of the present conception of the origin of monomineralic rocks. The rocks are intricately banded in such a manner as to lead Harker to suggest the intrusion of a non-uniform magma, implying apparently a non-uniform liquid.[2] A difficulty in the way of accepting this interpretation is that connected with obtaining a non-uniform liquid, especially with

[1] While it has been necessary in applying the foregoing tests to set aside anchi-monomineralic rocks containing a considerable amount of other minerals, it should not be assumed that there is any essential difference in the method of formation. These are merely examples in which accumulation of crystals of one kind has not taken place to quite the same degree and which consequently could have had a considerable amount of interstitial liquid.

[2] "Geology of the Small Isles of Inverness-shire," *Mem. Geol. Survey Scotland*, 1908, p. 74.

such extremes of composition. There is no promising method of doing so. Another difficulty presents itself in the very rapid changes from one type to another. Even granting some method of obtaining a heterogeneous liquid, one encounters the problem of maintaining these sharp contrasts in adjacent liquids, for diffusion, though unquestionably a slow process, would nevertheless accomplish much through moderate distances in the time required for the cooling of such masses. On the other hand, it seems reasonably possible both to obtain and to maintain almost any degree of heterogeneity as a result of the accumulation of crystals. On this assumption it is necessary to imagine the source of the olivine-rich types in a portion of the magma reservoir where olivine crystals had accumulated and of the feldspar-rich types where feldspar crystals had accumulated. These partly crystalline masses were thrust into the position where found. The greater the approach to monomineralic composition, the less liquid there could have been. In accordance with this conception it is found that in the allivalite the feldspar crystals are arranged with their elongation in the direction of flow of the sheets, and that this becomes more marked the richer the rock is in feldspar. In the case of bands consisting almost entirely of one mineral, which should have had very little liquid to lubricate their flow, it is found that characters consequent upon this are developed. Thus the nearly pure feldspar rock is described by Harker as strongly fissile and the pure olivine rock as foliated.[1] Possibly connected with the nearly solid condition of these rocks as injected is the fact that their intrusion apparently involved overthrusting, at least it is intimately connected with a line of overthrusting along which earlier, later, and possibly contemporaneous movements took place.

In correspondence with the unusual conditions of formation and intrusion of these ultra-basic rocks we find them to be scarcely duplicated elsewhere. The Russian ultra-basic rocks described by Duparc and Pearce seem to be their nearest relatives. They show a not dissimilar banding of closely related types and possibly may be explained in a like manner. The peridotite dikes are described as

[1] *Op. cit.*, pp. 72 and 87.

"parfois légèrement schisteux."[1] It may be noted at this point, also, that an augitite associated with the perfectly massive alkaline types of the Ice River district, British Columbia, is described as having a "suggestion of a schistose texture."[2] Observations such as these, though seemingly unimportant, may nevertheless have considerable importance in connection with the movement of a mass with very little interstitial liquid. It may well be, also, that in the movement of a mass with a small amount of interstitial liquid lies the secret of the formation of some monomineralic masses of extreme purity. Such movement when it caused a crushing of crystals at their points of contact would necessarily imply a flowing away of some liquid. Continuance of this action might, under certain conditions, result in a squeezing out of the interstitial liquid as from a sponge.

Rocks made up almost exclusively of albite or oligoclase are known, but there is usually evidence, if only of a collateral nature, that solutions have played a prominent part in their formation. Though often occurring as dikes there is never any reason for believing that these materials have ever been molten as such. And so it is with many masses of magnetite, indeed it is not impossible that practically any mineral might occur as dikes having a similar character and origin. Such an occurrence need not, however, affect one's belief that, as a rule, monomineralic rocks are crystal accumulations analogous to the great anorthosite masses and having the characteristics corresponding thereto.

It will be noted that nowhere in the foregoing discussion has an appeal been made to the remelting of the masses of crystals once accumulated. While the writer would not go the length of stating that such action never takes place, he would nevertheless consider that it must be of very exceptional occurrence. It has been shown that the monomineralic rocks are best explained without the aid of the doctrine of remelting, and many of the broader generalizations of igneous geology are opposed to it. For example, the parallelism between sequence of intrusion and sequence of con-

[1] "L'Oural du nord I," *Mem. soc. phys. et d'hist. nat. de Genève*, XXXIV (1902), Fasc. 2, p. 101.

[2] Warren, Allan, and Conner, *Am. Jour. Sci.* (4), XLIII (1917), 75.

solidation is altogether too close to permit one to consider remelting an important factor. Remelting would almost certainly destroy all law and order in this matter. Harker has recently expressed a belief to the contrary, pointing out that the remelting of a solidified mass with basic material at the bottom and acid at the top might take place from the bottom upward.[1] Possibly it might, and in an undisturbed crust it would realize the common sequence of intrusion, but in an earth's crust subject to faulting, folding, and overthrusting it may be doubted whether any regularity would be observed. Disturbance of the stratified mass would often put some of the basic material on a level with or even on a higher horizon than some of the acid material. The remelting of such a disturbed mass would not give rise to any significant regularity in the intrusive sequence.

A CONSIDERATION OF THE CRITERIA FOR THE RECOGNITION OF ONCE MOLTEN ROCKS

If we pass in review the development of ideas concerning igneous or once molten rocks we find them first clearly recognized in surface lavas. It was natural that it should be so, for here we have rocks that, judging from their relations to their surroundings, have evidently flowed as a liquid, and that are being duplicated in flows from active volcanoes at the present day. Then we find a few coming to believe that other rocks, usually quite distinct in appearance and occurring as deep-seated masses only bared by erosion, really are made up of the same material, the difference in appearance being principally due to the difference of conditions under which solidification took place. After much controversy this belief gains general acceptance, especially as a result of the accumulation of facts proving the essential identity of these deep-seated masses with volcanic flows. Originally, then, it was this correspondence of plutonic rocks with volcanic rocks that gave geologists the right to consider them once molten or igneous rocks. Simultaneously with the development of this view numerous facts corroborative of it accumulated, important among these being the manner in which the plutonic masses sent tongues into the surrounding rocks, and

[1] *Journal of Geology*, XXIV (1916), 556.

the light which the microscope threw on the process of crystallization of their mineral constituents, which evidently took place precisely as it should if they were once molten. Eventually, these corroborative facts came to be the criteria for the recognition of an igneous or once molten rock and, at present, in actual practice it is almost exclusively on the basis of the microscopic structure that a rock is placed as igneous or not. Thus judged, the monomineralic rocks are unquestionably to be considered as once molten, but if we revert to the original criteria we find that in some respects they fail to qualify. In the matter of sending tongues into surrounding rocks we find them scarcely typical, and as far as occurrences as lavas are concerned we find them wholly wanting. This apparent discrepancy is due to the fact that we have not made our distinctions fine enough. These rocks were formerly molten, but they were never molten as such. When molten they were part of a complex solution. Monomineralic rocks therefore afford the strongest justification for believing that crystallization controls differentiation. If differentiation took place in magmas wholly liquid, it would seem that all plutonic rocks should have their effusive equivalents. An examination of any table of classification of igneous rocks on a mineralogic basis shows, however, a decisive tendency for plutonic rocks to vary more widely than do effusives, especially among basic rocks, and especially in this matter of running to marked richness in one mineral. This fact would have little significance if it were a fairly common feature of plutonic rocks to lack an effusive equivalent, but it becomes of the greatest significance in connection with the manner of origin here advocated for the monomineralic rocks when it is realized that in this respect the monomineralic rocks stand alone.

VOLUME AND AGE RELATIONS OF MONOMINERALIC ROCKS

Of the monomineralic rocks anorthosite is the only one that occurs in any great amount. The actual volume of pyroxenite and peridotite exposed at the surface of the earth appears to be insignificant.[1] On account of the exceptional period required for the

[1] Daly's figures would indicate the order of magnitude (*Igneous Rocks and Their Origin*, p. 44).

sorting of plagioclase crystals anorthosite can form only from very large masses of magma that cool with great slowness, or if from masses of more moderate size these must be deep-seated. The anorthosite of the large masses normally belongs below the granitic zone so that, whether formed in very large bodies or in bodies of more moderate size, it is an especially deep-seated rock. Peridotites and pyroxenites by reason of the relative ease of sorting of these heavy minerals can form from moderate masses and at moderate depths, and are therefore of widespread occurrence and of general distribution in the geologic column though never exposed in large masses. Anorthosites, on the other hand, being essentially deep-seated are exposed only in terranes that have suffered, locally at least, exceptionally deep erosion, the pre-Cambrian and perhaps early Paleozoic. According to the writer's opinion there are probably large masses of peridotite and pyroxenite, but these have not been exposed at all for the same reason that anorthosite is exposed only in the older terranes. These peridotites and pyroxenites are, as it were, the complements of the granites, which in virtue of their low density are so abundantly exposed. Many will, no doubt, consider the opinion that there are large unexpected masses of pyroxenite and peridotite a pure assumption, and it is quite true that some assumption must be involved in the formation of opinion concerning inaccessible portions of the earth. Nevertheless, an assumption based on analogy with many completely accessible bodies showing density stratification should surely be given a preference over an assumption, tacit or otherwise, that the kind of rocks exposed in any body extend downward indefinitely, which is based merely on lack of evidence, one way or the other, for that particular body. However this may be, it is certain that anyone who believes that anorthosite is a differentiate of gabbroid magma, as most petrologists do, must believe that there is an equivalent amount of pyroxenite somewhere, and if not exposed then presumably in inaccessible regions. At this point the hypothesis of crystal accumulation steps in with a rational explanation of the not infrequent lack of pyroxenite in anorthosite terranes, very difficult to account for on the doctrine of liquid differentiation. Being an accumulated mass of crystals, pyroxenites usually remain sub-

stantially where formed. If liquid they could not fail to be represented very prominently in all anorthosite terranes, for the liquid would be freely intruded into overlying rocks at every disturbance experienced by them.

SUMMARY

Anorthosites are made up almost exclusively of the single mineral plagioclase, and in virtue of this fact they present a very special problem in petrogenesis. The conception of the mutal solution of minerals in the magma and the lowering of melting temperature consequent thereon is no longer applicable. Yet anorthosites give no evidence of being abnormal in the matter of the temperature to which they have been raised, in other words, they give no evidence of having been raised to the temperature requisite to melt plagioclase. A possible alternative is that they may never have been molten as such, and are formed simply by the collection of crystals from a complex melt, probably gabbroic magma. This possibility is in harmony with the expectations that grow out of experimental studies and for this reason a consideration of the likelihood that anorthosites have originated in the stated manner becomes imperative.

A consideration of the method whereby accumulation of plagioclase crystals might take place leads to the conclusion that the most promising is the separation by gravity of the femic constituents from gabbroid magma, while the plagioclase crystals, which are basic bytownite, remain practically suspended. Then, at a later stage, when the liquid has become distinctly lighter, having attained diorite-syenite composition, the plagioclase crystals, which are now labradorite, accumulate by sinking and give masses of anorthosite, at the same time leaving the liquid out of which they settle of a syenitic or granitic composition.

Some of the consequences of this manner of origin of anorthosite are as follows. Typical anorthosite, very poor in bisilicates, should not occur as small dikes, for a mass of accumulated crystals should have little invading power. A proportion of about 15 or 20 per cent bisilicates or other foreign material such as orthoclase and quartz should be necessary for the formation of small dikes. Typical anorthosite should for like reasons not occur as an effusive

rock, a rather large proportion of minerals other than plagioclase being necessary before such an occurrence would become possible. Anorthosite should be intimately associated with gabbro, but perhaps as intimately with syenite or granite. Anorthosites should commonly be labradorite rocks rather than bytownite or anorthite rocks.

A consideration of anorthosites with special reference to the Adirondack and Morin areas gives some reason for believing that anorthosites do show the requisite characters. For the Adirondack area especially, evidence is adduced favoring the possibility that there anorthosite and syenite may still occupy the relative positions in which they were generated by the process outlined, the Adirondack complex being interpreted as a sheetlike mass with syenite above and anorthosite below.

Other monomineralic rocks present essentially the same problem and are restricted in their occurrence in substantially the same manner if we consider especially those that approach most closely to the strictly one-mineral character. All of the monomineralic rocks do occur, however, as dikes and dikelike masses in essentially contemporaneous, congeneric, igneous rocks, a fact that may be interpreted as due to the intrusion of a heterogeneous, partly crystalline mass.

On the whole the inquiry gives considerable support to the belief that the monomineralic rocks, of which the anorthosites are perhaps the most important representatives, are generated by the process of collection of crystals under the action of gravity.

THE MIDDLE PALEOZOIC STRATIGRAPHY OF THE CENTRAL ROCKY MOUNTAIN REGION

C. W. TOMLINSON
University of Chicago

PART II

STRATIGRAPHY—*Continued*

UPPER CAMBRIAN AND EARLY ORDOVICIAN

Members 0 and 1.—Throughout western Wyoming, and at least as far north as Livingston, Montana, the thin-bedded upper part of the Gallatin formation rests upon a very massive cliff-making dolomite (Member 1), ranging up to 400 feet or more in thickness. Near Three Forks this member constitutes the "mottled limestone" (middle division of the Gallatin formation) of Peale,[1] which was correlated by Weed[2] with the Pilgrim limestone of the Little Belt Mountains. It corresponds roughly in position and in general character to the Hasmark formation, which was differentiated by Emmons and Calkins[3] in the Philipsburg quadrangle, Montana, and tentatively correlated by them with the Pilgrim.

Underlying this massive member in Wyoming and Montana is a zone of weaker strata (Member 0) in which green shales predominate, interstratified with thin beds of dolomite and flat-pebble limestone conglomerate. This belt includes the "*Obolella* shales" of Peale[4] in the Three Forks quadrangle, and at least the upper part of the Gros Ventre shale of Blackwelder[5] in western Wyoming; and is probably represented in the Park shale of Weed[6] in Montana.

[1] A. C. Peale, "Description of the Three Forks (Montana) Sheet," *Geol. Atlas U.S.*, Folio 24 (1896).

[2] W. H. Weed, "Geology of the Little Belt Mountains, Montana," *U.S. Geol. Survey, 20th Ann. Rept.*, Part 3 (1900), Pl. 40, opp. p. 284; p. 286.

[3] W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Survey, Prof. Paper 78* (1913), pp. 57–59, 63.

[4] *Op. cit.* [5] Eliot Blackwelder, unpublished manuscript. [6] *Op. cit.*, p. 286.

The upper part of the Cambrian sequence in Utah is not unlike that in Wyoming. There is a very prominent massive member (No. 1), which is overlain by thin-bedded dolomites (Members

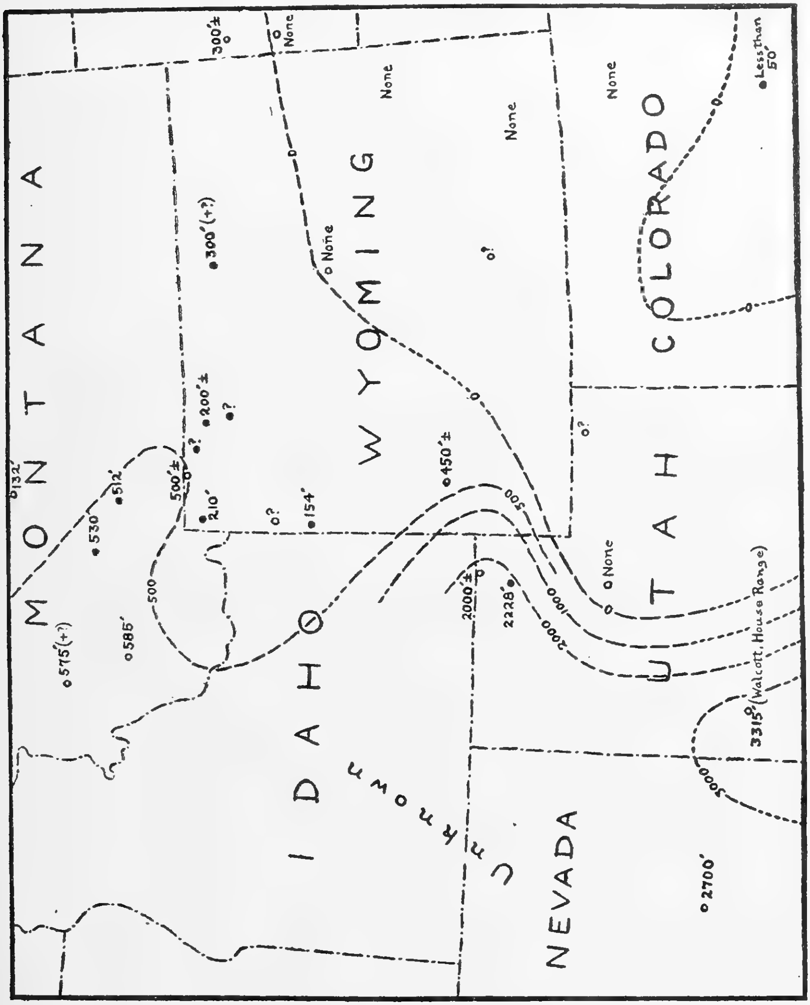


FIG. 6.—Map showing the extent and thickness of the Upper Cambrian and Early Ordovician series (Members 1 to 4, inclusive).

2–4) containing a great deal of flat-pebble limestone conglomerate, and is underlain by a series (Member 0) of thin-bedded dolomites with considerable clastic sediment and a minor constituent of

flat-pebble conglomerate. Walcott[1] places the lower boundary of the Upper Cambrian approximately in the middle of this lower series (Member o), at the base of a sandstone member. No fossils have been found in the 1,000 feet of beds (Nounan formation) next beneath that horizon, but the Bloomington formation, next below, carries a Middle Cambrian fauna.[2] As the shales of Member o in Montana and Wyoming have been assigned to the Middle Cambrian, they are possibly to be correlated with the green shales of the Bloomington formation.

Members 3 and 4 in northern Utah.—The main flat-pebble conglomerate series (Member 3) on Blacksmith Fork is 800 feet thick, and has yielded fossils at several horizons. These collections have established the Ordovician age of all but the lower 190 feet of the member, which is left by Walcott[3] in the Upper Cambrian. The Garden City formation in the Randolph quadrangle is described by Richardson[4] as containing flat-pebble conglomerate throughout its estimated 1,000 feet of thickness, but it may include a representative of Member 4 as well as of Member 3. Richardson's collections[5] are like those of the writer from Member 4 on Blacksmith Fork, and clearly indicate that this formation is of Beekmantown age, possibly ranging up into slightly later time.

Richardson[6] states that he has evidence of an unconformity between Cambrian and Ordovician, but this evidence is not yet published. Elsewhere in Utah no evidence has been cited of an interruption in sedimentation at this horizon, and it is certain, as indicated by the exact similarity between the latest Cambrian and the earliest Ordovician rocks, that if similar conditions were not continuous from the former period into the latter in this region they returned with very little modification after the interruption. The upper record succeeds the lower without the intervention of any clastic sediments.

[1] C. D. Walcott, "Cambrian Cordilleran Sections," *Smithsonian Misc. Coll.*, LIII (1910), 193.

[2] Walcott, *op. cit.*, pp. 194–95.

[3] *Op. cit.*, p. 191.

[4] G. B. Richardson, "The Paleozoic Section in Northern Utah," *Amer. Jour. Sci.*, 4th Ser., XXXVI (1913), 406–15.

[5] *Op. cit.*, pp. 408–9.

[6] *Op. cit.*, p. 408.

Correlation with the Pogonip group of Nevada.—The Pogonip group of the Eureka district of Nevada, called Lower Silurian by Hague[1] and Walcott,[2] probably includes equivalents of the Garden City formation and part or all of the St. Charles formation (Upper Cambrian, Blacksmith Fork). The upper part of the Pogonip group carries a fauna, considered by Walcott[3] to be of Chazyan age, which bears a notable resemblance to the faunas of the Garden City formation.

Member 3 in Wyoming and Montana.—In Wyoming the thin-bedded Upper Cambrian–Lower Ordovician(?) sequence, including flat-pebble conglomerate, is nowhere represented by more than 500 feet of strata, but its characters are typical of Member 3 wherever it is exposed. In southwestern Montana it forms the highest member of the Gallatin formation.

The faunas so far collected from this sequence in both Wyoming and Montana are very meager, a fact which has made its correlation a subject of dispute in various localities. In the Bighorn Range, Member 3 constitutes the uppermost part of the Deadwood formation, which is called by Darton[4] Middle Cambrian; but the only species Darton names as coming from the upper 600 feet of the formation (about 1,000 feet thick in all) is *Dicellomus politus*, which is associated in one locality[5] with fragments of a trilobite resembling *Ptychoparia oweni*. Some collections from the upper part of the Gallatin formation in western Wyoming, comprising three species of *Eoorthis* and some fragmentary trilobite remains, have been referred to the Upper Cambrian by paleontologists of the United States Geological Survey.[6] Member 3 probably is represented

[1] Arnold Hague, "Geology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs*, XX (1892).

[2] C. D. Walcott, "Paleontology of the Eureka District," *U.S. Geol. Survey, Monographs*, VIII (1884).

[3] *Op. cit.*, pp. 3–4.

[4] N. H. Darton, "Geology of the Bighorn Mountains," *U.S. Geol. Survey, Prof. Paper 51* (1906), p. 26.

[5] N. H. Darton, "Fish Remains in Ordovician Rocks in the Bighorn Mountains, Wyoming, with a Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 551.

[6] Eliot Blackwelder, personal note. Cf. C. D. Walcott, "Cambrian Brachiopoda," *U.S. Geol. Survey, Monographs*, XXXI (1912), 233, Lot 302*e*.

in the Red Lion formation (250 feet thick) of the Philipsburg quadrangle, Montana, from which Kindle[1] has made some collections identified by Walcott[2] as Upper Cambrian.

The beds in question probably are equivalent to some part or parts of Member 3 of the Utah sequence, and it is therefore possible that they may include strata of Lower Ordovician age.

The Maxfield formation of the central Wasatch.—Hintze[3] has described a sequence of 481 feet of limestones and shales "disconformably overlying the Alta shale"[4] on the South Fork of Big Cottonwood Canyon, southeast of Salt Lake City, which he has named the Maxfield formation, and has tentatively assigned to the Ordovician. The Alta shale (150–200 feet thick), which rests on the basal Cambrian quartzite, carries a Lower Cambrian fauna near its base and a Middle Cambrian fauna at a higher horizon.[5] Disconformably above the Maxfield lies the Devonian Benson limestone.

No fossils have been found in the Maxfield formation. Its reference to the Ordovician was suggested by the "wormy" appearance of the chief limestone members of the formation, which Hintze likened to the Lowville ("Birdseye") limestone of New York, and by the occurrence at the top of the formation of 10 feet of shale alternating with typical flat-pebble ("edgewise") limestone conglomerate, which Hintze[6] noted had been described from Lower Ordovician strata elsewhere. Unfortunately for this correlation, conglomerate of that type is abundantly developed in northern Utah, not only in the Garden City (Beekmantown) formation, but in the St. Charles (Upper Cambrian) and Bloomington (Middle Cambrian) formations. The "wormy" appearance is to be seen in various members of each and all of the six Middle and Upper

[1] E. M. Kindle, "Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bull. Amer. Pal.*, No. 20, 1908, pp. 10–11; also Emmons and Calkins, *op. cit.*, p. 63.

[2] C. D. Walcott, *op. cit. ult.*, p. 233, Lots 302*q*, 302*r*.

[3] F. F. Hintze, Jr., "A Contribution to the Geology of the Wasatch Mountains, Utah," *Annals New York Acad. Sci.*, XXIII (1913), 85–143.

[4] *Ibid.*, p. 105.

[5] C. D. Walcott, *U.S. Geol. Survey, Bull. No. 81*, 1891, p. 319.

[6] *Op. cit.*, p. 106.

Cambrian formations at Blacksmith Fork, but has not been noted in the Garden City formation. Amounts of shale comparable to that in the Maxfield (about 180 feet, all told) are present only in the Langston, Ute, and Bloomington formations at Blacksmith Fork.

Furthermore, flat-pebble conglomerate is abundant throughout the lower 600 feet (about half) of the Garden City formation at Blacksmith Fork, but has not been noted in the upper half of the formation there at all. The relation noted in the Maxfield formation, of 480 feet of interbedded shales and limestones with flat-pebble limestone conglomerate in the upper 10 feet only, could thus not be matched in the Garden City formation. A sequence almost precisely similar to that of the Maxfield formation does occur, however, in the Bloomington formation.

The Maxfield formation of the central Wasatch, therefore, is probably of Cambrian age, and bears a striking likeness to the Middle Cambrian Bloomington formation of the Bear River plateau, 75 miles farther north.

The close relation of the Canadian series to the Upper Cambrian series.—If the upper limit of the Cambrian system in northern Utah has been defined correctly, the changes which took place between Canadian (or Chazyan) and Trenton time in the Rocky Mountain–Great Basin paleogeographic province were more notable than those which occurred between Upper Cambrian and Canadian time in that region. The latest sediments assigned to the Upper Cambrian are of the same type as the Canadian deposits, whereas the sediments of Trenton age are very different from either of the former. The erosion preceding the beginning of Trenton sedimentation is known to have been extensive, whereas evidence of erosion between Upper Cambrian and Canadian time is reported from only one locality.

The physical evidence thus goes to show that the affinities of the Western Canadian are rather with the Cambrian than with the higher Ordovician.

Is the Ozarkian system represented here?—If the Ozarkian period of Ulrich is represented in the western province, it must be by some part of the Upper Cambrian–Lower Ordovician sequence above

described. In the absence of an adequate description of the fauna of the typical Ozarkian, it is difficult to make comparison therewith. The base of the Ordovician was placed by Walcott[1] at Blacksmith Fork at the first appearance of cephalopods. As determined by Richardson[2] in the Randolph quadrangle, the base of the Garden City formation there is marked by the appearance of several genera of coiled gastropods. The post-Cambrian, pre-Swan Peak (see below) series thus defined has a thickness on Blacksmith Fork of 1,272 feet, which is 68 per cent greater than the total thickness of the overlying Ordovician, including the Richmond. As above noted, Richardson describes a marked unconformity at the top of the Cambrian in the Randolph area. These faunal distinctions and this physical evidence may warrant the recognition of the series in question as a separate system; but there is no evidence yet at hand to suggest its subdivision into *two* systems, Ozarkian and Canadian. It is possible that the St. Charles formation includes a representative of the former.

Up to the present, however, the Ozarkian has not been recognized in the Rocky Mountains.

THE ORDOVICIAN QUARTZITES AND SANDSTONES

The Eureka and Swan Peak quartzite.—In eastern Nevada the unfossiliferous Eureka quartzite, ranging from 200 to 500 feet in thickness, lies in apparent conformity upon the Pogonip limestone. The upper surface of the Eureka quartzite is clearly an irregular erosion surface. It is overlain by the Lone Mountain limestone, which carries a Trenton fauna near its base.[3]

The Eureka quartzite corresponds closely in stratigraphic relations to the quartzite at Geneva[4] and to the Swan Peak[5] quartzite, both in northern Utah, which attain a similar thickness. Unconformity is evident above the Swan Peak quartzite in the Randolph quadrangle,[6] and farther south the post-Swan Peak erosion locally

[1] C. D. Walcott, "Cambrian Cordilleran Sections," *Smithsonian Misc. Coll.*, LIII (1910), 191.

[2] *Op. cit.*, pp. 408–9.

[3] Hague, *op. cit.*, pp. 58–59.

[4] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, XXI (1910), 526–27.

[5] Richardson, *op. cit.*, p. 408.

[6] *Ibid.*

resulted in the complete removal of the quartzite, so that in the section exposed on Blacksmith Fork the succeeding dolomites of Trenton(?) age rest unconformably on the Garden City formation.

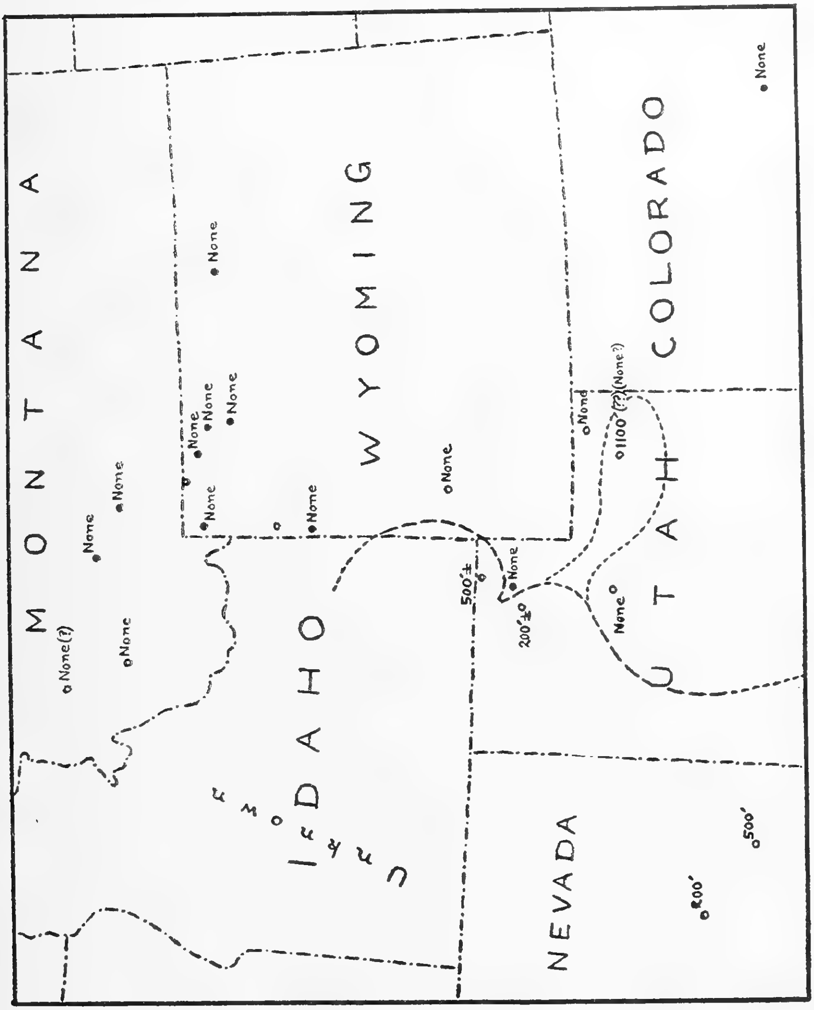


FIG. 7.—Map showing the extent and thickness of the Chazyan (?) quartzites

The Swan Peak quartzite contains a small fauna which has been referred tentatively to the Chazyan by Ulrich.[1] Four of the eight forms identified from the Swan Peak are found also in the similarly

[1] *Op. cit.*, p. 408.

meager fauna of the quartzite at Geneva.[1] There is no representative of these quartzites in the section described by Hintze[2] in Salt Lake County, Utah, 75 miles south of Blacksmith Fork.

The absence of the Swan Peak quartzite from the Blacksmith Fork section is especially notable in view of the fact that it occurs with a thickness of several hundred feet less than 20 miles to the northeast, in the Randolph area, and also less than 20 miles away in the opposite direction, near Geneva.

The "Ogden quartzite" in the Uinta Range.—In the south slope of the Uinta Range a quartzite attaining a maximum thickness of about 1,100 feet lies between the Mississippian system and the barren Lodore shales (Cambrian ?). Weeks[3] correlated this formation with that which is called in this paper the Swan Peak quartzite, in the region east of Cache Valley, Utah; and he applied to both formations the same name, "Ogden quartzite." As no fossils have been found in the "Ogden quartzite" in the Uinta Range, the correlation rests on an insecure basis.

No representative of this quartzite was noted on the north flank of the Uinta Range.

The sandstone at the base of the Bighorn formation.—The Trenton dolomites in Wyoming for the most part lie directly on the flat-pebble conglomerate series, but locally they are accompanied by a thin basal sandstone carrying a late Black River or early Trenton fauna, including fish remains.[4] This sandstone is correlated with the fish-bearing Harding sandstone of Colorado,[5] which likewise is overlain by dolomites of Trenton age. It is probable, as has usually been considered, that this sandstone member represents an introductory stage of the Trenton submergence rather than that it is a deposit of an earlier submergence, separated by an epoch of erosion from the Trenton proper, as is the case with the Swan Peak and Eureka quartzites. The faunal lists from the Swan

[1] Blackwelder, *loc. cit. uls.* [2] *Op. cit.*

[3] F. B. Weeks, "Stratigraphy and Structure of the Uinta Range," *Bull. Geol. Soc. Amer.*, XVIII (1907), 436–37, 441.

[4] N. H. Darton, *op. cit.* (1905), p. 551; and Bald Mountain–Dayton Folio, Wyoming, *Geol. Atlas U.S.*, Folio No. 141 (1906), p. 4.

[5] N. H. Darton, *op. cit.* (1905), p. 552; and Folio 141, p. 4.

Peak quartzite[1] and the quartzite at Geneva[2] include no species, and only two genera (*Orthis* and *Endoceras*) in common with the published lists of fossils from the Harding sandstone[3] and the basal Bighorn sandstone.[4]

THE MIDDLE AND UPPER ORDOVICIAN DOLOMITES

Extent of the Bighorn dolomite.—The Bighorn dolomite was named by Darton[5] from its characteristic exposures on both flanks of the Bighorn Range in northern Wyoming, and by him was correlated with the Whitewood limestone of the Black Hills and with the Fremont limestone of the Front Range of Colorado.[6] The same author later recognized the Bighorn dolomite in the Owl Creek[7] and Wind River[8] ranges of Wyoming. Fisher[9] briefly described its occurrence in Cedar and Rattlesnake Mountains, west of Cody, Wyoming. Blackwelder[10] has identified it in the Gros Ventre and Teton ranges, farther west.

The Bighorn dolomite in Montana.—Both Darton[11] and Fisher[12] prophesied that the Bighorn dolomite would be found to be included in the "Jefferson limestone" of Hague, and the truth of this

[1] Richardson, *op. cit.*, p. 410. [2] Blackwelder, *op. cit.* (1910), p. 527.

[3] N. H. Darton, "Fish Remains in Ordovician Rocks in the Bighorn Mountains, Wyoming, with a Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 563.

[4] *Ibid.*, pp. 554–56, footnote.

[5] N. H. Darton, "Comparison of the Stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain Front Range," *Bull. Geol. Soc. Amer.*, XV (1904), 379–448.

[6] N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.*, Folio 141 (1906), p. 4.

[7] N. H. Darton, "Geology of the Owl Creek Mountains," Fifty-ninth Congress, 1st session, Senate Document No. 219 (1906), p. 15.

[8] N. H. Darton, "The Paleozoic and Mesozoic of Central Wyoming," *Bull. Geol. Soc. Amer.*, XIX (1908), 403–74.

[9] C. A. Fisher, "Geology and Water Resources of the Bighorn Basin, Wyoming," *U.S. Geol. Survey, Prof. Paper 53* (1908), p. 12.

[10] Eliot Blackwelder, unpublished manuscripts, *U.S. Geol. Survey.*

[11] N. H. Darton, "Fish Remains in Ordovician Rocks in the Bighorn Mountains, Wyoming, with a Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 554.

[12] *Op. cit.*

prophecy has now been demonstrated by the writer's work. The Bighorn dolomite is characteristically developed throughout the length of the Absaroka Range, and has yielded Ordovician fossils

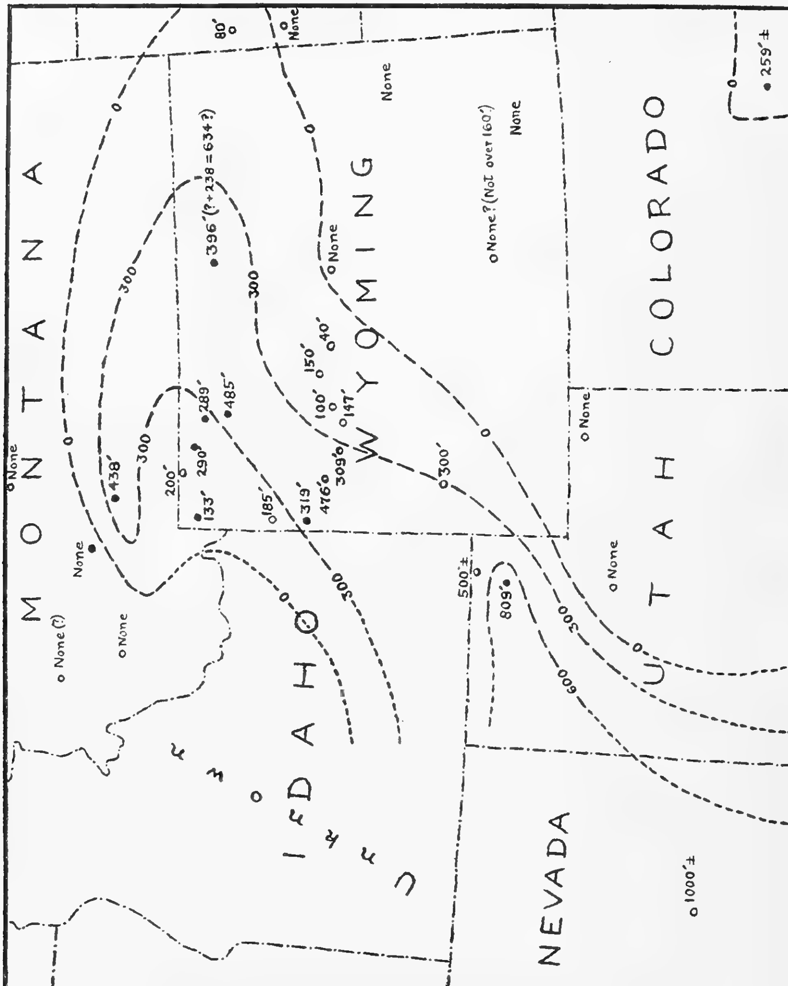


FIG. 8.—Map showing the extent and thickness of the Bighorn dolomite (Middle and Upper Ordovician) and correlated formations.

in the Crandall (Wyoming) and Livingston (Montana) quadrangles. It is a remarkable fact that, although this formation is 438 feet thick in Livingston Peak, it has no known continuation north of that point, nor west beyond the Gallatin Range.

Members 2–4.—There can be little doubt as to the validity of most of the correlations of Trenton strata shown in the preceding table and diagrams, except in Utah and Nevada. The main massive member (No. 4) of the Lower Bighorn, with its accompanying basal weaker strata (Members 2 and 3) and its cap of smooth, nearly chalky, dolomite, constitutes a highly characteristic and almost unique series. Furthermore, Member 2 is fossiliferous, and Member 4 is sparingly so in nearly all localities.

The upper half of the massive member in the Blacksmith Fork section, which the writer has called the Lower Fish Haven dolomite, is similar in all essential respects to the massive Trenton member of the typical Bighorn. It is marked off from the Richmond above by a conglomerate, and disconformity at its base is sufficiently indicated by the absence of the (Chazyan ?) quartzite which intervenes at that horizon elsewhere in northern Utah. This lower Fish Haven dolomite carries *Halysites*, which is not known from rocks older than Mohawkian.

The lower part of the Lone Mountain limestone, which unconformably overlies the Eureka quartzite in western Nevada, carries a fauna assigned by Walcott[1] to the Trenton. Ulrich[2] has voiced the opinion that part of the Lone Mountain limestone is older than the Bighorn dolomite; but it is probable that the former formation contains a representative of the Trenton series.

Members 5–7; the Leigh formation.—Members 5–7 of the Middle and Upper Ordovician series constitute a distinct and very widely developed unit. In the Goose Creek Ridge section there is little ground for differentiating these three from each other; but the lowest Richmond fauna occurs in the beds there marked as Member 6. In the Crandall Creek and Dead Indian Creek sections there is a conspicuous surface of disconformity, with a basal breccia, at the base of Member 6. As this is the only disconformity for which physical evidence has so far been noted anywhere within the limits of the Bighorn formation, and as it coincides (by lithologic correla-

[1] Arnold Hague, *op. cit.*, pp. 61–62, 196–97; also appendix by C. D. Walcott, pp. 324–25.

[2] Cf. Bailey Willis, "Index to the Stratigraphy of North America," *U.S. Geol. Survey, Prof. Paper 71* (1912), p. 169.

tion of beds both above and below) with the base of the known Richmond part of the Bighorn in the type locality, it probably represents the hiatus which was inferred by Darton between the Trenton and Richmond members of the Bighorn.

In the Teton Range, there is likewise an unconformity at the base of Member 6. Blackwelder[1] proposes the recognition of Members 6 and 7 in that region, and of corresponding strata in the Gros Ventre Range, as a distinct formation, to be called the *Leigh*, from its typical development on Leigh Creek, in the Teton Range. In view of the fact that this group of strata, in its type locality, is bounded both above and below by unconformity, and is lithologically quite distinct from the underlying massive member (Member 5 is not present in the Teton River section), its recognition as a separate formation seems justified. In the Absaroka Range the corresponding beds differ little in character from the upper part of the Trenton series (Member 5), but are marked off from it by unconformity, as just described.

Between Members 4 and 8 of the Livingston Peak section, light-colored dolomites of the Leigh type occur interbedded with darker, gray-brown, more coarsely crystalline dolomites. In the Blacksmith Fork section there is an interbedding of light and dark strata through a thickness of 130 feet above the conglomeratic horizon, which is taken as the probable base of the Richmond series. Above this sequence there is an 8-foot stratum corresponding closely to the typical Leigh in character, and directly underlying the main massive part of the Fish Haven, which is correlated with Member 8. The first sediments deposited after the pre-Richmond emergence seem to be more variable in character from place to place than are the strata above them, or the members of the Trenton series.

Members 8 and 9.—Member 8 is in some places, in lithologic characters, essentially similar to Member 4, but is in no case quite so thick as the latter. On Goose Creek Ridge there are only two 12-foot massive beds of this type, themselves separated by 20 feet of less resistant dolomites, between the typical Leigh (Members 6 and 7) below and the main fossiliferous, thin-bedded part of the

[1] Eliot Blackwelder, personal note.

Richmond series above. It is possible that the much thicker massive dolomite characterizing the Upper Bighorn in the Absaroka Range is equivalent to a part of this thin-bedded series (called Member 9), as well as to the underlying more massive beds. On Blacksmith Fork, Member 8 forms the main body of the Upper Fish Haven dolomite. In common with several other parts of the Ordovician system, it is somewhat darker in color there than in Wyoming.

The highly fossiliferous, thin-bedded dolomites (Member 9) of the Upper Bighorn in the Bighorn Range unfortunately are not typically developed elsewhere.

There is no representative of the Bighorn in Hintze's[1] section in the central Wasatch, nor in the Uinta Range.[2]

[1] F. F. Hintze, Jr., *op. cit.* [2] F. B. Weeks, *op. cit.*

A FEW INTERESTING PHENOMENA ON THE ERUPTION OF USU

Y. ŌINOUYE
Imperial Tohoku University, Sapporo, Japan

The eruptions of Japanese volcanoes for the past fifty years have been almost invariably of the Strombolian type. But recently there have been displayed five different types which may be listed as follows: (1) an appearance of a new volcanic island,[1] (2) a new lava dome in the crater of Tarumai, (3) 45 craterlets on the slope of Mount Usu, (4) ejecting lava up in the craters of Asama[2] and Mihara,[3] and (5) lava flows on Sakurajima. Partial descriptions of the Tarumai and Usu have been published by the writer,[4] while an account by Professor B. Koto of the third will appear in the near future.

In the southern part of Hokkaido, in North Japan, three volcanic eruptions took place between 1905 and 1910. Komagatake was in eruption in August, 1905, Tarumai in April, 1909, and Usu in July, 1910. A line connecting these three volcanoes lies in a northeast to southwest direction and represents the northern extremity of the Nasu volcanic chain. The three volcanoes mentioned are about equally distant from each other (48 km.). The explosion of Komagatake was simple and on a small scale, ejecting fragments around the crater and ashes around the foot of the volcano for a few days only, while that of the Tarumai[5] was more

[1] T. Wakimidzut, "Report on the Ephemeral Volcanic Island in the Iwojima Group," *Bulletin of the Imperial Earthquake Investigation Committee*, No. 56 (1907).

[2] F. Omori, *Bulletin of the Imperial Earthquake Investigation Committee*, VI, No. 1 (1912).

[3] Y. Okamura, *Bulletin of the Imperial Geological Survey of Japan*, No. 48 (1914).

[4] *Report of the Imperial Earthquake Investigation Committee*, No. 64 (1909). Official Report of Hokkaido Colonization (1910).

[5] Y. Ōinouye: *Report of the Imperial Earthquake Investigation Committee*, No. 64 (1911); H. Shimotomai, *Zeitschrift der Gesellschaft für Erdkunde zu Berlin*, No. 9 (1912).

severe. The Usu eruption is the latest one among the three, which was quite similar to that on Etna in September, 1911. This volcano is located between the other two, in longitude E. 140° 49′ 30″ and latitude N. 42° 33′, and lies between "Volcano Bay" on the south and Lake Toya (80 m. higher than sea-level) on the north. Usu is a low, conical, active volcano, 736 m. above the sea, and has a crater 2 km. in diameter, within which there are

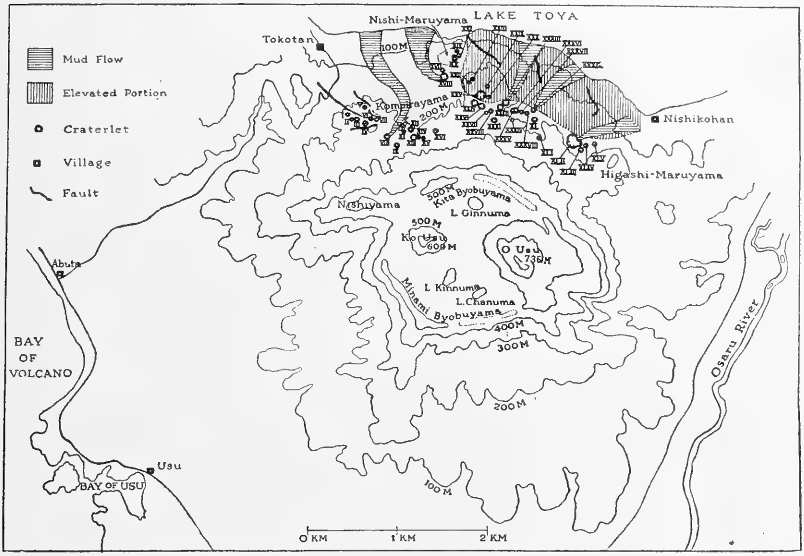


Fig. 1.—Map of Volcano Usu, showing craterlets on the northern slope

two domes occupying respectively the east and the west end of the crater (Fig. 1). The eastern of these domes, O-usu (736 m. AT), looks new, while the western one, Ko-usu (609 m. AT), appears much older. Ko-usu has a few small, steaming pits on the top of its dome, while O-usu has one only on the west side of its dome. The topography, geology, and history of Usu have been well described by Professors F. Omori[1] and D. Sato.[2] Hence only the especially interesting details of the eruptions will be discussed here.

[1] *Bulletin of the Imperial Earthquake Investigation Committee*, V, No. 1 (1911).

[2] *Bulletin of the Imperial Geological Survey of Japan*, XXIII, No. 1 (1913).

I. EARTHQUAKES AND ROARINGS

Preceding the eruption there were frequent earthquakes, seeming to repeat the past history of the mountain, which has always exhibited the "foreshocks" in advance of an eruption. But the writer believes that the occurrence of so many earthquakes in the neighborhood of a volcano within the limits of Japan is a rare phenomenon. It was rumored that slight earth movements were

FIG. 2.—A fissure on the road near Abuta

noticed six days before the eruption. But, as observed by a few persons, the first earthquake began on the evening of July 21, four days in advance of the eruption, and successive earth tremblings were felt from the morning of July 22, continuing through the eruption and for two months thereafter. Numbers of these quakes were felt at Nishimombetsu, 8.4 km. southeast of Usu, 25 on July 22, 110 on July 23, 354 on July 24, 163 on July 25, and thereafter in gradually decreasing numbers. It was on the evening of July 25 that the first eruption took place, and, after it had relieved the strains to some extent, the quakes began to decrease in number.

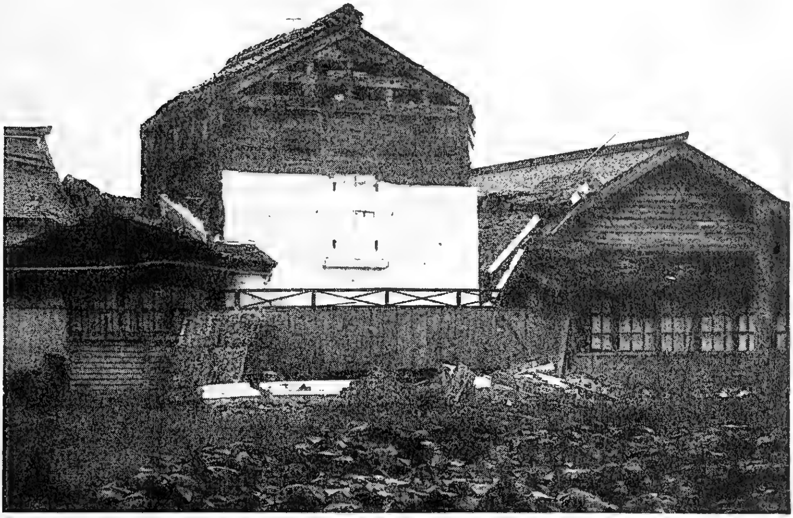


FIG. 3.—A house destroyed by the severe earthquake at 4:30 P.M. on July 24, 1910

FIG. 4.—A monument shaken down by the severe earthquake at 4:30 P.M. on July 24, 1910.

The report of the Municipal Office and the members of the Meteorological Observatory of Sapporo and Hakodate give the numbers in Table I.

TABLE I

NUMBER OF EARTHQUAKES OBSERVED AT NISHIMOMBETSU

Date	Violent	Strong	Weak	Tremor	Total
July 22....	....	....	13	12	25
23....	....	8	48	54	110
24....	1	28	134	150	313+40.5*
25....	1	19	58	85	163
26....	....	1	11	16	28
27....	....	3	14	5	22
28....	....	6	3	8	17
29....	....	1	2	9	12
30....	....	1	3	1	5
31....	....	....	2	1	3
August 1....	....	....	2	4	6
2....	....	....	....	2	2

* Lack of observation for three hours. The number is estimated by means of an average for the three preceding and the three following hours.

From hourly observations the following results were obtained.

From July 22, 7:00 A.M., to July 23, 7:00 P.M., 36 hrs., 66 quakes, 1.8 per hr.
From July 23, 7:00 P.M., to July 25, 8:00 A.M., 37 hrs., 533 quakes, 14.4 per hr.
From July 25, 8:00 A.M., to July 25, 10:00 P.M., 14 hrs., 48 quakes, 3.4 per hr.

The writer's visit to Mount Usu was made on the afternoon of July 24, amid the climax of the quaking. At that time the quakes occurred rather oftener than once in five minutes. The houses trembled so from the subterranean violence that the windows rattled continually throughout the entire day, and made so much noise that no one could stay within the houses. It was noticed that every quake was preceded by the sound which seemed to come from deep within the earth, or as if heavy artillery were being fired in the distance. But sometimes on the east side of the mountain, or in the direction of Volcano Bay, probably owing to the echoes, the same sound was heard. It frequently happened that the sound was first heard in the distance; then a landslide was seen on the dome of O-usu; and following almost immediately the quivering of the earth was felt. A year previous, when the writer visited Usu, a small column of steam was seen to rise from the small pit on the west side of O-usu, and this was the same in

FIG. 5.—The largest mud cone at Usu village. Taken July 30, 1910

FIG. 6.—Numerous mud cones in the Bay of Usu. Taken July 30, 1910

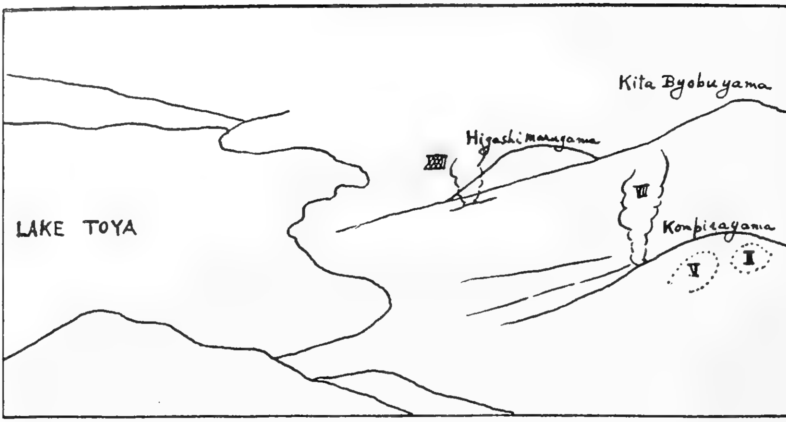
FIG. 7.—A fault of 1 m. throw, at the west foot of the Kompirayama. Taken August 2, 1910.

FIG. 8.—The same fault which has increased its throw to 2 m. Taken September 4, 1910.

amount when the second visit was made during the time of the eruption under discussion. The surrounding country was noted

FIG. 9.—The first explosion crater on the Kompirayama. Taken July 26, 1910

to be the same topographically as it had been on the previous visit. Judging from the history of this volcano, the writer recognized



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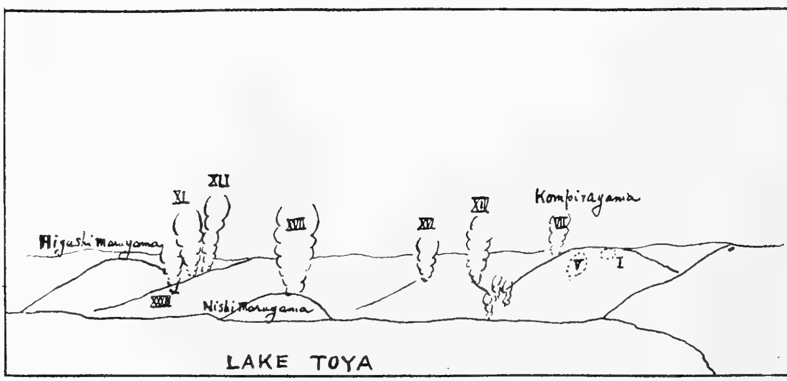

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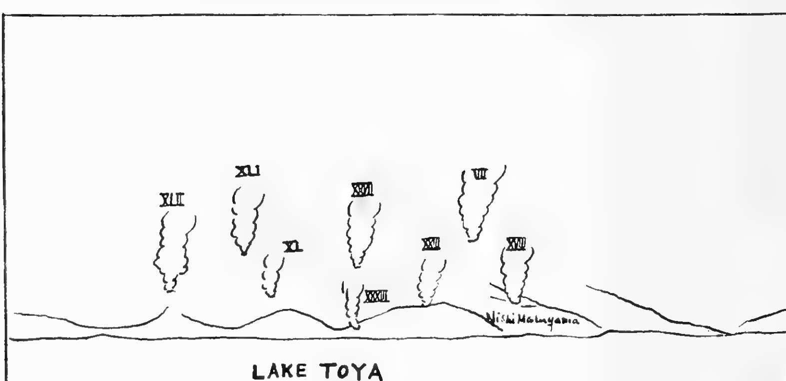

c

FIG. 10*a*.—A sketch of craters from the west. 5:00 P.M., July 27, 1910
FIG. 10*b*.—A sketch of craters from the northwest. 11:20 P.M., July 28, 1910
FIG. 10*c*.—A sketch of craters from the north. 6:00 P.M., July 29, 1910

that the preliminary warnings were the symptoms of an eruption, and, watching the crater every moment during the day and night and the following day, he observed in detail the phenomena. The number of earthquakes, as well as their vigor and intensity, increased. No one could indulge in sound sleep in the neighborhood of the volcano. Cannonading and trembling developed till the introductory explosion took place. Among the several hundred

FIG. 11.—A great column of smoke at the top of Nishimaruyama beyond the steaming mud flow. Taken August 2, 1910.

earthquakes two violent ones are worthy of mention, one at 4:30 P.M. on July 24, and the other at 5:00 P.M. on July 25. Monuments fell, houses were badly damaged, the earth was ruptured, and many mud cones were formed around the volcano (Figs. 2–6). The earthquake wave reached an average radial distance of 65 km. outward from Usu, except in the southwesterly direction, where it reached 140 km. The earth's shaking abruptly decreased after the first explosion, suggesting that strains which had been accumulating were then relieved.

II. EFFECT OF THE EARTHQUAKES

There were several phenomena of interest due to the preliminary earthquakes, such as fissures, faults, and the building of mud cones.

1. *Fissures.*—Many ruptures were made within the circle of severe shaking of the earth, especially on the west side of the

FIG. 12.—South scarp of "graben" at the top of Kompirayama. Taken July 14, 1911.

volcano. The directions of the fissures were almost parallel to the coast line, i.e., northwest to southeast, and their width was from 3 cm. to 40 cm. (Fig. 2). Close to the mountain, on the west side, the direction changed to east-west.

2. *Faults.*—Two distinct faults extending east and west were made on the west foot of the Usu. Stepping down toward the north (downthrow side on the north), the throw of the southern fault measured 30 cm. and that of the northern one 1 m. The former extended about 50 m. and the latter 600 m. in length. On September 2 an additional throw of 1 m. was noticed, developing

numerous small parallel fault fractures besides showing 2 m. of horizontal shifting (Figs. 7 and 8).

3. *Mud cones.*—The mud cones are small mounds of mud and sand, well stratified and laminated. They range in size from several centimeters to three meters in diameter, and are flat and conical in shape, the angle of slope being from 3 to 16 degrees. The smallest cone seen measured 10 cm. in diameter, and the largest

FIG. 13.—North scarp of "graben" at the top of Kompirayama. Taken July 14, 1911.

5 m. (Fig. 5). The height of the former was 3 cm. and that of the latter 60 cm. Great numbers of such cones were formed in the bay at the southwestern foot of the mountain, distributed irregularly upon the tidal flat (Fig. 6). About 200 m. from the shore line there is a row of such cones trending generally northwest-southeast. While this row of cones is roughly parallel to the shore line, and consequently fairly straight, there are numerous bends in the line. From the structure of the cones it follows that there must have been a periodical eruption of the sand and mud. The laminations, ranging from 5 mm. up to 3 or 4 cm., are roughly proportional

to the size of the cone, the thicker laminae being found in the larger cones. As is usual with all the cones of this region, it was cold water that issued from them before the eruption of the volcano.

On the north side of Usu a few cones were found on the flat farm land at the foot of the mountain. At no other place in the neighborhood were these phenomena observed. All the cones were

FIG. 14.—Step fault at the west foot of Kompirayama. Taken August 18, 1910

formed by the first severe earthquake, which occurred at 4:30 P.M. on July 24, 1910. The phenomenon is not a peculiar one, for such cones have been reported at many places where strong earthquakes have taken place. They are invariably located along the crack formed by the earthquake where the ground-water issuing through the newly opened vent brings sand and mud with it to the surface. After the eruption of the volcano the mud cones ceased to be active and were gradually obliterated by the process of erosion.

4. *Rise of the water-level in near-by wells.*—Practically all the wells in the neighborhood of the volcano showed a rise in the

water-level; very few showed a decrease. In most cases it was noted that the water in the wells increased to about double the normal volume, while at the same time it became turbid and dirty, owing to the particles of dry mud which fell from the wells into the water below. The rivers of the region also became brown and turbid from slumping of the clay banks. On the southeast side of the mountain several new springs were formed which are still flowing.

III. EXPLOSIONS

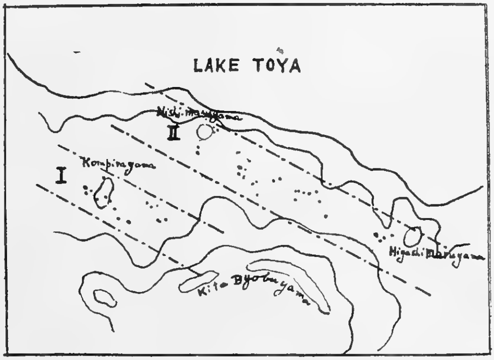

FIG. 15.—Two groups of craterlets. Group I is located at the southwest of Group II.

After July 22 frequent earthquakes took place, their intensity and numbers increasing hour by hour till 10:00 P.M. on July 25, when the first explosion took place on the northwest side of Kompirayama, a parasitic cone, on the northwest slope of the main volcano (Fig. 9). For a few hours red-hot bombs were ejected on the north side of the cone and made numberless holes in the roofs of the houses in the near vicinity. When the writer visited the region on the following morning, the vent was entirely free from escaping steam, making it possible for him to descend into the crater. At 2:13 P.M. on July 26, a second explosion, preceded by roaring and trembling, took place 200 m. southeast of the first crater accompanying two small explosions. This explosion ejected black and white smoke to a height of about 700 m. That night the smoke stopped for a few hours, but again, beginning at three o'clock in the morning, the roaring became louder and louder as of strong thunder near by, till four o'clock, when it gradually subsided. Meanwhile frequent earthquakes accompanied the formation of three or four explosion craters. In the afternoon of the next day, July 27, the writer saw the ejection of smoke in two craters east of the crater mentioned above (Fig. 10*a*). At 7:00 A.M.

on July 28, roaring again began, and two explosions took place in sight of the writer at 11:20 A.M. (Fig. 10*b*). The loud roaring continued till eight o'clock in the evening. On the same day there was heavy rain all day accompanied by loud thunder, intense lightning, loud roaring in the ground, and much dense smoke hiding the mountain entirely from view. Before 9:00 A.M. on July 29, judging from the numbers of smoke vents found on that morning, several more explosion craters were formed (Fig. 10*c*).

FIG. 16.—A group of craterlets on the second group. Taken September 4, 1910

On August 2 two new craters were formed at the top of Nishimaruyama, a parasitic cone. For a week these two craters poured forth an astonishing amount of smoke in a large black column such as was not seen from any other cone (Fig. 11). The volume suddenly decreased at the end of one week. Thus in the period of greatest activity, from July 25 till August 2, the number of craters formed amounted to 15. Thereafter, on August 7 and 8, on September 3, and on October 2, small explosions occurred, so that the total number of craters reached 45. Besides these craters numerous crevices and faults developed on the side of the moun-

tain. At the top of the small parasitic cone, Kompirayama, a "graben" was formed about 30 m. in maximum depth, 100 m. wide, and roughly 500 m. in length (Figs. 12, 13). Westward, across the road, the same faulting was found to be "step faulting," with the northern blocks downthrown (Fig. 14). It seems apparent, therefore, that the northern fault of the "graben" is a "scissor fault," reversing its throw on crossing the road. Close to the second group[1] of craterlets, at the same time, were formed many

FIG. 17.—Mud-flow from crater No. VII. Taken August 2, 1910

faults, among which were some forming fault scarps of 5–7 m. in height. The trend of both systems of faults is west-northwest by east-southeast. It is noteworthy that such a large number of craterlets formed in the ten weeks of the eruption.

1. *Process of explosion.*—The order of formation of these craterlets was as follows: In the beginning a cannon-like sound was heard, the ground cracked open in a straight line in the form of a V-shaped crack (Fig. 9), and white smoke issued from the vent. Then followed black smoke together with sand and ashes.

[1] See Fig. 15.

This is the normal order of eruptions for all the craters. The ashes and bombs ejected from the fissures upon the sides of the crevice, after a day, or at most a few weeks, built up a cone. The rapidity with which the cones were built depended on the size of the orifice and the amount of ejectamenta. The angle of slope of the cones ranged from 15 to 30 degrees, the steeper ones being made of the rather coarse material. As the cones grew, the old vents became quiescent and new ones broke out on the side of the

FIG. 18.—"Puff cones" on the mud-flow. Taken August 19, 1911

cone, and the ejectamenta, filling the old crater, sometimes obliterated it.

The life-history of the different cones was not the same, some of them becoming quiescent after only one explosion, others continuing for several days to roar and emit black smoke and to build cones. Some of them emitted smoke intermittently, being active for a few days and then quiet for a few days and then active again, etc. Besides the smoke, ashes, sand, and bombs, a large amount of mud[1] flowed from five of the craters.

[1] *Jour. Geol.*, XXIV, No. 6.

2. *Explosion craters.*—The 45 craters are arranged in two groups (Fig. 15). The first, consisting of 16 craters lying north-northwest of Mount Usu, is aligned in a west-northwest to east-southeast direction. The second group, lying 800 m. northeast of the former, is composed of 29 cones lying in a line parallel to the first group (Fig. 16). The altitude, date of formation, size, shape, and the life-history etc., of each cone in the two groups are tabulated in Table II.

Fig. 19.—Ejection of smoke from crater No. XLII. Taken August 3, 1910

The formation of the cones apparently has no order, though a few in the first of the groups described above formed in sequence, starting from the northwestern end and proceeding toward the east. But in general the action was begun in the first group and finished in the second group.

3. *Ejectamenta.*—Ash, sand, and bombs, with SO_2 and H_2S, were ejected in the black smoke and carried to the lee by the wind, some of the ashes quite a distance. From the first explosion ashes were carried 44 km. toward the northwest of the Usu. Later, ashes from a later eruption were carried 4 km. toward the east and 20 km.

TABLE II

No.	Date	Time	Order	Altitude	Crater			Cone		Remarks
					Shape	Diameter	Depth	Height	Slope	
				m		m	m	m		
I	Aug. 8	2:30 P.M.	13	225	Round	15	5	15	30°	
II	Aug. 8	?	13	245	Round	15	7	7	30	
III	Aug. 8	?	13	250	Round	31	15	0	0	Steaming until May, 1911
IV	July 26	2:13 P.M.	2	270	Ellipse	36×30	13	0	0	
V	July 25	10:00 P.M.	1	240	Ellipse	91×13	18	0	0	Issues smoke and ejects ashes and bombs for a few hours
VI	July 26	2:13 P.M.	2	275	Round	24	9	0	0	Smoke high up to 1,000 m.
VII	July 26	2:13 P.M.	2	275	Ellipse	42×33	10	0	0	
VIII	July 28		5	205	Round	22	2	7	30	Mud-flows
IX				220	Ellipse	36×22	13	0	0	
X				220	Round	10	7	0	0	
XI				220	Round	18	9	0	0	
XII				190	Round	15	15	0	0	
XIII	July 29	8:00 A.M.	9	240	Round	91	35	0	0	Emits black smoke daily until beginning of August
XIV				255	Round	45	16	0	0	
XV				255	Round	16	5	0	0	
XVI	July 27	3:00 A.M.	4	250	Round	27	9	4	20	Crater opens toward west
XVII	Aug. 8	Morning	12	160	Round	36	14	9	26	
XVIII	July 28	5:30 P.M.	7	160	Round	100	18	0	0	Crater opens toward west and mud-flows in great quantity
XIX	Aug. 2	3:00 A.M.	11	160	Round	18	7	0	0	Big black smoke for a week
XX	Aug. 2	3:00 A.M.	11	160	Round	23	9	0	0	Big black smoke for a week
XXI	Aug. 2	3:00 A.M.	11	160	Ellipse	40×18	16	0	0	Big black smoke for a week
XXII				210	Ellipse	69×18	32	0	0	Still steaming
XXIII	July 29	5:00 A.M.	8	210	Ellipse	82×42	16	0	0	
XXIV				240	Round	93	40	9	20	Most active in the beginning of September
XXV	Oct. 2		14	220	Round	130	80	0	0	The second largest crater and the most active
XXVI	July 29	5:00 A.M.	8	250	Round	84	38	18	32	Most active in the beginning of September
XXVII	July 28	5:30 P.M.	7	250	Ellipse	50×47	24	18	25	
XXVIII				240	Ellipse	50×36	11	20	24	
XXIX				230	Ellipse	27×15	7	0	0	
XXX				220	Round	90	18	5	20	
XXXI				250	Round	51	29	31	30	Much ejectamenta, and completes the cone on August 13
XXXII				210	Round	76	40	15	20	Steaming on the north wall in the crater
XXXIII	July 26	11:30 P.M.	3	205	Round	64	30	18	18	Mud-flows on July 29, and still steaming
XXXIV				200	Round	31	9	18	28	
XXXV				200	Ellipse	70×20	18	10	20	
XXXVI				200	Ellipse	85×70	37	0	0	More active than XXXV and XXXVII, and overlaps them by ejectamenta
XXXVII				190	Ellipse	54×22	11	0	0	
XXXVIII				190	Round	69	37	23	32	
XXXIX	July 27	3:00 A.M.	4	165	Ellipse	62×40	6	15	25	Mud-flows and partly overlapped by ejectamenta of XXXVIII
XL	July 28	11:20 A.M.	6	175	Ellipse	69×40	10	0	0	
XLI	July 28	11:20 A.M.	6	220	Ellipse	70×60	30	10	20	Crater opens toward east
XLII	July 29	9:00 A.M.	10	220	Ellipse	210×150	90	50	30	Three craters unite and make the largest pit, mud-flows and the most active
XLIII	July 29	9:00 A.M.	10	170	Ellipse	70×24	11	0	0	Crater opens south
XLIV	July 29	9:00 A.M.	10	160	Round	22	7	0	0	
XLV				155	Ellipse	20×10	9	0	0	

toward the south, the amount being greatest on the northwest side of the mountain. In the Kompirayama region the ashes that fell formed a layer up to 8 and 10 cm. in thickness, while at the distance of 1 km. from the mountain thicknesses of 3 mm. to 1 cm. were found. On the north side of the second group of cones, a general thickness of 1 cm. was found, while at their very foot the layer was 30 cm. in thickness. But on the east side and south side of the mountain

FIG. 20.—Bombs and mud-flow from crater No. XLII. Taken July 31, 1910

very little ash was found. Besides the ash, sand, and bombs, from five of the craters mud and hot water were ejected. Among these five craters No. VIII was the first to erupt (Fig. 17), while No. XIII ejected the largest quantity of mud (Fig. 11). From the craters to the lake is an expanse of mud which flowed out to a width of 200 m., a length of 500 m., and a thickness of 1.5 m. In addition to this great quantity of mud on the land there was a large amount that flowed into the lake. The mud is composed of fine, gray-colored plagioclase, hypersthene, augite, and magnetite, with a

small amount of hematite, together with glass in an amount comparable with that of the feldspar. Cone No. XVIII ejected the mud periodically in a geyser-like fashion. The mud contained a large amount of gas which came to the surface of the mud-flow after it had almost solidified, making "puff cones"[1] in great numbers (Fig. 18).

The materials of the mud-flows, the sand of the seashore, and the substance in the mud cones mentioned above, when compared

FIG. 21.—Heavily burdened trees near the craters. Taken October 16, 1910

under the microscope, were found to be identical in composition. The fineness, however, is variable; the size of grains in the beach sand being the largest, that in the mud cones intermediate, and that in the mud-flow the finest. The base of the volcano Usu is composed of brown pumice, uniform in constitution throughout the whole region, and the fact that the mud-flows, the cones, and the sand of the beach are alike in composition suggests that they all came from some common source, which in all probability lies horizontally and extends not much below the level of the sea.

[1] *Jour. Geol.*, XXIV, No. 6.

From craters Nos. XXV and XLII great quantities of bombs and sand were intermittently ejected to a height of 700 m. (Figs. 19, 20). The ejected bombs and ashes frequently took the shape of serrate peaks and pinnacles which rose alternately to great heights and then sank back as another one shot up. It was noticed that descending bombs, when struck by rising ones, produced loud reports like the explosion of firecrackers. White, comet-like tails followed the bombs into the air. The largest bomb measured

FIG. 22.—Houses inclined 12° owing to the elevation of the left-hand side. Notice a man standing straight. Taken September 4, 1910.

was 25 cm. in diameter and was of the characteristic irregular and rounded shape. The largest hole noted, formed by a falling bomb, was 3 m. in diameter by 2 m. in depth.

Petrography of the bombs (augite-hypersthene-andesite).—The bombs ejected from the several craterlets are quite similar, though the percentages of the constituent minerals are slightly different. A brief description follows:

Megascopically, the bombs are dark gray, porous, roundish in shape, and less than 25 cm. across. The pores are very abundant at the surface, slightly less numerous within, and range in diameter

from 1 mm. to 2 cm. The majority of the pores are filled with ashes and sand. Phenocrysts of white plagioclase, which do not exceed 3 mm. in size, produce a porphyritic texture. There are also crystals of dark-colored pyroxene, but they are small and not abundant.

Microscopically, the rock has a hyalopilitic-porphyritic texture. The groundmass consists of dark-brown glass with minute crystals

FIG. 23.—New elevated mountain seen from the east. Taken December 23, 1910

of plagioclase, augite, and hypersthene, and the phenocrysts of colorless plagioclase and green pyroxenes.

Plagioclase is the chief constituent. It is either tabular or equidimensional, and polysynthetic twins and zonal structures are remarkably well developed. Zonally or irregularly included in some of the crystals are patches of brown glass and minute grains of pyroxene.

The extinction angle on the *M* face of the plagioclase is between -28° and -30°, and the maximum extinction angle in the symmetrical zone is $+32^\circ$, showing it to be labradorite.

The hypersthene has a slender prismatic habit and strong pleochroism, green to reddish brown.

Augite is usually small in size, mostly in the groundmass.

The rock may be formulated as follows:

$$\frac{P_{40}}{G_{60}}=\frac{\text{Lab.}_{28}+\text{Hyp.}_{8}+\text{Aug.}_{4}}{\text{Glass}_{36}+\text{Lab.}_{18}+\text{Hyp.}_{3}+\text{Aug.}_{3}}$$

P_{40}, 40 per cent of phenocryst.

G_{60}, 60 per cent of groundmass.

Lab., labradorite.

Hyp., hypersthene.

Aug., augite.

Chemical composition.—The rock is rather basic, low in SiO_2, high in Al_2O_3, CaO, and iron, so that some might call it basalt. The writer found a great similarity in mineralogical and chemical composition between the bomb and the lava which forms the old crater ring of the main volcano, as shown by Table III, which gives an analysis of the bombs, with other similar rocks for reference.

TABLE III

	I	II	III	IV	V	VI	VII	VIII
SiO_2	52.40	51.86	51.88	51.32	50.16	52.02	52.86	51.12
Al_2O_3	17.59	21.69	21.53	17.84	17.97	17.14	18.25	19.59
Fe_2O_3	3.51	4.46	2.45	4.34	2.23	7.96	6.61	2.86
FeO	7.07	5.39	6.36	6.70	6.25	3.52	3.39	6.53
MgO	3.73	2.87	2.08	4.18	4.70	3.13	4.27	4.47
MnO	0.16	0.29	0.20	....	0.30	tr.	0.16	0.65
CaO	9.36	10.37	11.09	9.51	11.85	11.57	9.58	9.54
K_2O	1.77	1.08	1.56	1.52	2.80	0.60	0.69	0.57
Na_2O	2.93	2.02	3.12	3.01	3.50	2.38	3.24	3.11
H_2O	0.57	0.26	0.17	1.98	....	0.28	0.69	0.11
TiO_2	1.06	....	....	....	....	....	....	0.86
P_2O_5	0.14	....	....	....	....	....	....	0.14

I. A bomb from Usu, analyzed by *Bulletin of the Imperial Geological Survey of Japan*, XXIII, No. 1.
II. Mean value of three bombs, analyzed in the laboratory of geology in the Agricultural College, Sapporo.
III. Lava of old crater ring on Mount Usu, analyzed in the same laboratory.
IV. Luciite, Luciberg, Odenwald Hesse.
V. Augite-andesite, Kilauea, Hawaii.
VI. Basalt? Yate Volcano, Patagonia.
VII. Pyroxene-andesite, Choa-shen, Kamchatka.
VIII. Basalt, Goentoer lava, Java.
III to VIII taken from J. P. Iddings, *Igneous Rocks*.

IV. DAMAGE

By the fracturing of the earth and the explosions, the deep, beautiful forest on the slopes of the mountain was destroyed. The leaves were all stripped from the trees, the greater number of

which were broken and shattered. Many were blown out of the ground by the explosion, while others were buried and broken by the fall of bombs and ashes (Fig. 21). The bombs, however, were not thrown more than 500 m. from the craters, but the sand and ashes were driven to a distance of several kilometers. Often heavy showers of sand and ashes were seen to fall in localized areas, in many places forming long strips of débris on the land. At one place in a field of barley the strip measured 3 m. wide and was traced for a distance of 200 m. While in the air these masses of ejectamenta looked like a jet of water issuing from a hose. This effect was produced by air currents concentrating the material into long lines. The damage done by falling ash, including injury to farm land as well as destruction of houses, etc., was heavy within a radius of 2 km. of the craters. The most severe damage by ash and mud-flow amounted to 3 sq. km. of land covered. Five houses were carried down to the lake by the mud-flow, and a few houses were buried by the heavy ashes, while five other houses were shattered as a result of the local undulation of the land. At Abuta, a distance of 4 km. from the nearest crater toward the northwest, a monument and a small house fell, together with three brick walls (Figs. 1, 3, 4) and two plaster ones of a storehouse. In the same village many cracks developed in the walls of the houses.

V. CHANGE OF TOPOGRAPHY

On July 28 the writer found the rise of the water of Lake Toya on the north side to be about 30 cm. On August 6 Dr. Omori found a lowering of the water-level on the south side of the lake. From August 20 it was noticed that the north side of the second group of craters began to rise. This elevation (155 m. high from the lake-level, according to Professor F. Omori) continued till the end of November. The slope of the southern shore of the lake was about 5 degrees. It then gradually rose to a slope of 30 degrees at the top of the elevation, and 22 degrees on its flank. A photograph taken by the writer on September 4 shows a house which, originally constructed upright, was then inclined 12 degrees from the vertical. Two days later this house had collapsed (Fig. 22). Before the

eruption the cone Nishimaruyama could be seen from the village of Nishikohan, but as a result of the elevation which took place the view was obstructed. The area of elevated land is about 2 km. in length by 1 km. in width to the edge of the lake, and, judging from soundings made, it extends another kilometer under the water (Fig. 23). The maximum height of the elevation measured about 120 m. (Figs. 24, 25, 26).[1]

FIG. 24. Mountain slope in the beginning of eruption. Taken July 29, 1910

Mr. Ito, of the Sapporo Meteorological Observatory, found a lowering of 36 m. on the top of the new mountain in April, 1911, while Mr. Iizuka, of the Imperial Geological Survey, recorded 43 m. lowering in July, 1911, by an aneroid barometer.

When the gases involved in the lava are expelled in a great quantity, a decrease of volume will take place, and the lowering of the mountain should result from this shrinkage.

[1] This measurement was made by comparing graphically and to scale the photograph taken before the elevation with that taken afterward. This checked well with the reading of the aneroid barometer which nearly coincides with the map of the Imperial Geological Survey of Japan.

Furthermore, there is a remarkable change of height in Usu proper, as is shown by the map of the Imperial Geological Survey, July, 1911. In the topographical map published by Hokkaidocho, the height of O-usu is recorded as 595 m. and that of Ko-usu as 580 m., while the Imperial Geological Survey reports 736 m. and 609 m. respectively. This difference is too great to be regarded as an error in surveying and must mean that some igneous intrusion produced the irregular change of elevation. The writer presumes that the present height of Usu would be found to differ materially from that recorded by the Imperial Geological Survey.

One year after the eruption Dr. Omori[1] observed that there were local elevations and depressions of the ground in the vicinity of the mountain and over an area of 150 sq. km. The Military Survey Department undertook the determination of height at the request of Dr. Omori and found that Mount Usu was raised, while the western foot was depressed. In the following year the same surveyor recorded contrary results; that is, the previously elevated portion had been depressed, while the depressed part was uplifted.

VI. SUMMARY

1. *Earthquakes and roaring before an eruption.*—As a rule the eruption of Usu is preceded by the foreshocks. This, in the opinion of the writer, suggests that the lava reservoir was located nearly at the same depth in the case of the recent eruptions. The magma in the reservoir, becoming highly heated, could not retain the involved gases, and so the maximum strain under the crust was produced by the continuous heating process. The explosion took place when the interior and exterior pressures were not counterbalanced. Thus the pressure of the highly heated magma overbalanced both the atmospheric and the crustal pressures. The ground beneath the surface burst, owing to the intense strain, and produced the loud sound. The speed of the earthquake waves is greater than that of the sound traveling in the ground and the air. The minute tremor which normally precedes the sound was not noticed because there was no seismograph at hand. Hence,

[1] *Bulletin of the Imperial Earthquake Investigation Committee*, V, No. 3 (1913).

in a seemingly contradictory fashion, the large tremor of the earthquake was felt after the sound was heard.

2. *Least resistance.*—From the structural point of view the greatest number of fractures were observed along the sides of the great depression, or along the anticlinal top; and especially large fractures were found close to the edge of the depression. On the coast line of the Pacific Ocean the presence of several volcanic

FIG. 25.—"New Mountain" almost completed. Taken October 25, 1910

zones naturally demonstrates the existence of fractures made by the depression of the Pacific basin. Two recent faults in the vicinity of Usu were made by the earthquakes, many fractures usually accompanying the fissures along the aperture. Coming back to the original Lake Toya, the writer believes that the depression of the ground produced the lake, which is surrounded by comparatively sharp cliffs; as T. Kato stated in his report,[1] there must have been some fractures along the margin of the lake through which Mount Usu erupted. Such fissures, the writer dares to say,

[1] *Report of the Imperial Earthquake Investigation Committee*, No. 62.

are the weak lines around the foot of Mount Usu. The gases involved within the magma found an exit through the old fissures, the lines of the least resistance, which existed under the lava-flow, and thus the two fissure zones, parallel to the shore line of the lake, were made. As in the case of a viscous substance which is being boiled and shows the evolution of gases in certain restricted points which migrate around over the surface of the liquid, we may assume that the gases evolving from the magma are generated at different

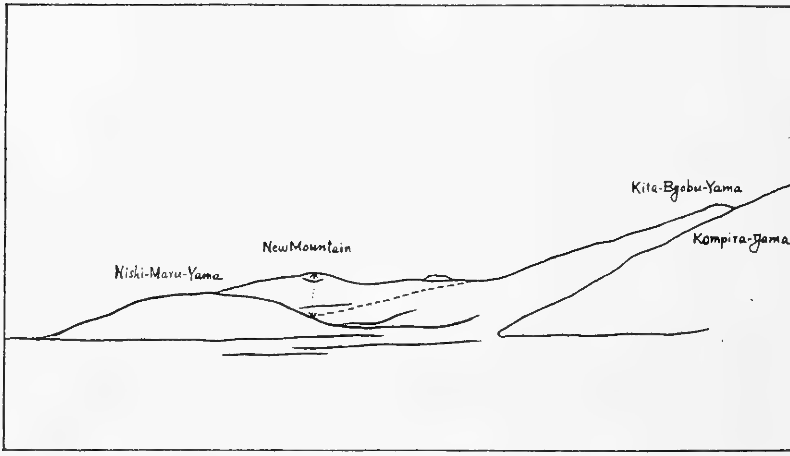

FIG. 26.—Topographical comparison of the north side of the Usu. Broken line, the slope before the elevation. Taken July 29, 1910. Full line, the present relief. Taken October 25, 1910. Dotted line, the actual difference of altitude.

places without reference in time to each other. The irregular eruption of the craterlets may be explained on this hypothesis.

The independent activity of the new craterlets to the old, small, steaming pits on the O-usu and Ko-usu suggests by their lack of sympathy that they do not rise to the surface through the same lava vents and that the reservoirs are not connected.

3. *Origin of the "New Mountain."*—Professor F. Omori[1] stated that the "New Mountain" is due to the intrusion of lava in the form of a spine or dome, and Professor D. Sato[2] believes the intru-

[1] *Bulletin of the Imperial Earthquake Investigation Committee,* V, No. 1, p. 1.

[2] *Bulletin of the Imperial Geological Survey of Japan,* XXIII, No. 1 (1913).

sion to be a laccolith. Many geologists agree with the theory of G. K. Gilbert as to the formation of the laccolith. It is a plausible supposition that the propelling magma would find the line of least resistance in certain planes, lifting the land above it. In the early stages of the activity in Mount Usu enormous quantities of gases were emitted, together with ashes and bombs, while at the mature stage the north side of the second zone of craters was sharply elevated in a straight line. Ernest Howe[1] made experiments on the intrusion of wax into plaster, marble, sand, and coal layers, and demonstrated how the laccoliths are formed. Where there are fissures from the inner source to the surface, there must be a line of least resistance at this place. Intrusion between the strata occurs only where there are no fissures or cracks extending to the surface. It is unreasonable to believe in the intrusion of the laccolith while the distinct cracks shown in the two zones of craterlets are in evidence, as we have seen in the experimental data of Howe. The majority of nearly 150 laccoliths in the western part of the United States of America are composed rather of acidic rocks, while rock[2] as basic as that of Usu is found only in rare cases. The basic lavas preserve a comparatively high degree of liquidity down to rather low temperatures, with a quick process of solidification by rapid crystallization, as is well illustrated in blast-furnace slag. Ejection of many bombs demonstrated that the lava was not seated in the great depths.

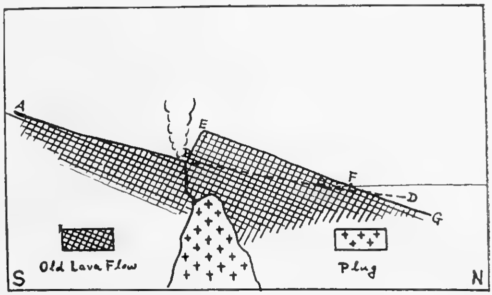

FIG. 27.—A diagram showing the intrusion of "plug": *A, B, C, D,* mountain slope before the eruption; *B, E, F,* elevated mountain; *C,* shore line before the eruption; *F,* present shore line.

From the facts stated above, the writer is inclined to believe that the formation of a "plug," elongated west-northwest by east-

[1] *Twenty-first Ann. Rept., U.S.G.S.,* Part III (1901).

[2] See the analysis of bomb.

southeast and elliptical in plan, took place in the midst of the activity. Of course, we must not forget that the elevation is not entirely due to the intrusion of the plug, but that there was co-operation of the faulting such as is so remarkably shown on the top of Kompirayama. The elevation of the lake shore on the south side of Lake Toya may be accounted for by the tilting of the crust owing to the intrusion of the plug rather than, as previously supposed, to the formation of a laccolith (Fig. 27). From dynamic considerations it is evident that if the force of the plug intrusion be applied to one end of a resistant section of the earth's crust the whole block will be lifted and tilted.

How could such a very steep slope (40°–70°) on the south side and 22°–30° on the north side be made on the surface by the intrusion of a laccolith? If we suppose that there is a very sharp, steep dome in the great depth overlaid by heavy layers above, its inclination becomes gradually gentle toward the surface, unless the crust be in the liquid or semiliquid condition.

4. *Undulation of ground near Usu.*—From the damage done, and from faults, fissures, and mud cones which were found exclusively on the same side, we may prove that the structure of the western region was originally weak, so that the shaking was intense, while in other parts the effects were comparatively small. Frequent explosion also weakened the already feeble lines.

We may then conclude, from evidence gathered in the field, that there must have been intruded irregular bodies of lava that produced the undulation of the ground near Usu recently observed in the eruption.

INTRAFORMATIONAL PEBBLES IN THE RICHMOND GROUP, AT WINCHESTER, OHIO

AUGUST F. FOERSTE
Dayton, Ohio

Ripple-marks, measuring two feet or more from crest to crest, occur at numerous horizons in the Ordovician rocks of Ohio, Indiana, and Kentucky, but are abundant especially in the middle parts of the Richmond group, where they characterize the upper part of the Waynesville formation and the lower part of the immediately overlying Liberty formation. Among the occurrences of ripple-marks discussed by Prosser, in his recently published paper on the "Ripple-Marks in Ohio Limestones,"[1] the following belong to the lower part of the Liberty formation: Elk Run, a little over a mile east of Winchester, Ohio (Figs. 1, 2); Cherry Fork, at Harshaville, 6 miles east-southeast of Winchester; and Treber Run, 5 miles southeast of Harshaville. The ripple-marks described by Joseph Moore and Allen D. Hole from a small western tributary of the Whitewater River, 5 miles southwest of Richmond, in Indiana, and those described by W. P. Shannon from the bed of Salt Creek, 3 miles west of Oldenburg, 38 miles southwest of Richmond, also occur in the lower part of the Liberty formation. At the Ridenour Mill, $5\frac{1}{2}$ miles northwest of Oxford, Ohio, the ripple-marks described by Nelson W. Perry[2] occur both in the lower part of the Liberty and in the upper part of the underlying Waynesville formation. In fact, over a large part of Ohio and Indiana, ripple-marks are fully as abundant in the upper part of the Waynesville as in the lower part of the Liberty, and the list of localities might be multiplied almost indefinitely. Ripple-marks occur also near the top of the Brassfield formation at numerous localities in southern Ohio (Figs. 3, 4) and northern Kentucky, east of the Cincinnati axis.

[1] *Jour. Geol.*, XXIV, No. 5 (1916), pp. 456–57.

[2] *Am. Geol.*, IV (1889), 326–36.

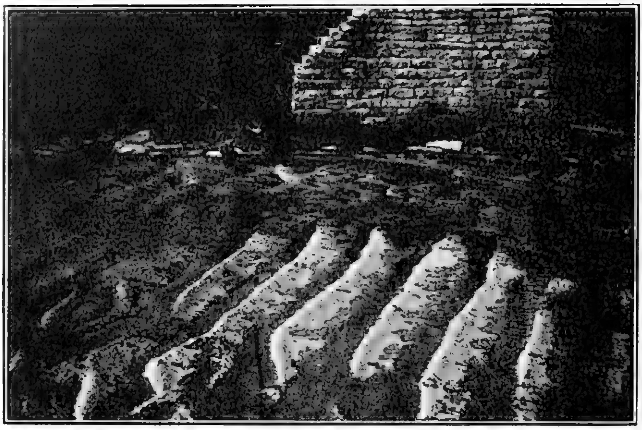

FIG. 1.—View of ripple-marked limestone in bed of Elk Run, looking northward toward abutment of road bridge. The appearance of strong contrast in the slope on opposite sides of the ripples is due to the dip of the rock toward the right causing the water to rise higher on the left side of the crests. In reality, the difference in slope on the two sides is small.

FIG. 2.—View at the same locality, looking northeast across the stream. See also Fig. 2, on p. 460 in *Journal of Geology*, XXIV, No. 5 (1916).

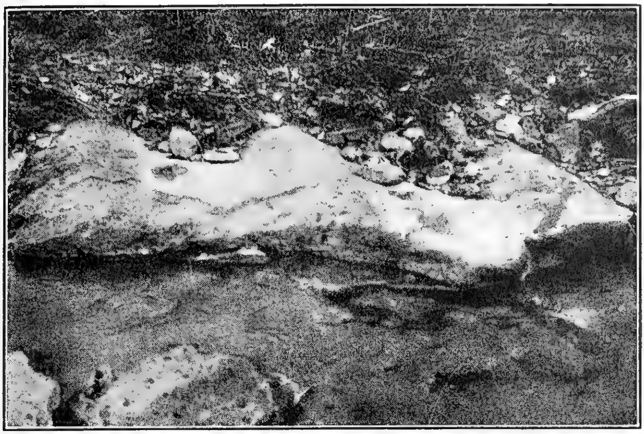

FIG. 3.—Ripple-marks on Brassfield limestone in Beasley Fork, a mile and a quarter south of West Union, Ohio. Note the small difference in slope on the two sides of the ripples.

FIG. 4.—Ripple-marks at the same locality and horizon on Beasley Fork

Occasionally pebbles occur in the ripple-marked layers of limestone. These pebbles usually are few in number and rarely are sufficiently abundant even to suggest the term conglomerate. They are more abundant at two horizons in the lower part of the Liberty formation at the locality on Elk Run, east of Winchester, Ohio, described by Prosser, than at any other localities known at present in the Ordovician of Ohio, Indiana, and Kentucky, and therefore this locality has been chosen to present some of the features characteristic of these pebbles. The pebbles are of two types.

1. In one type the rock is very fine-grained, as though originating from a calcareous mud, and is frequently marked by worm-burrows. There are also peculiar gouged-out markings, 3 or 4 mm. wide, 60–100 mm. long, often 20 mm. deep at the center, curving downward from the ends toward the center as though carved out by some narrow gouge. Markings of this kind frequently connect the two oblong or nearly circular terminals forming the peculiar dumb-bell fossil called *Arthraria*. There are also gouged-out markings only an inch in length (Fig. 6, pebble *C*). The surface of these pebbles often is very irregularly rounded, as though the rock had been soft at the time of formation of the pebbles. At one horizon these pebbles frequently support small colonies of the incrusting coral *Protarea richmondensis* (Fig. 5), 40–70 mm. in width. In fact, twenty pebbles supporting *Protarea richmondensis* were exposed along a narrow outcrop, a foot wide and scarcely 50 feet long, at the time of my last visit. Young specimens of *Streptelasma*, presumably *Streptelasma rusticum*, 10–15 mm. in length, occasionally occur, attached by their sides to the pebbles. Three pebbles supporting young specimens of *Streptelasma* occurred in the 50-foot length mentioned above. Incrusting growths of *Dermatostroma corrugata* and of various thinly incrusting bryozoans also occur occasionally. Since the incrusting growths follow the irregular curvature of the pebbles, it is evident that the latter is not due to subsequent erosion. In one specimen, thinly incrusting bryozoans and growths of *Stomatopora* occur on the lower side of the pebble, while thicker growths of *Protarea richmondensis* occur on the upper surface, showing that the pebble had been turned over at least once.

The fine-grained mud of which these pebbles are composed incloses but few fossils. In three pebbles *Lophospira bowdeni* was found, and one pebble contained a ventral valve of *Dinorthis subquadrata*, a characteristic fossil of the Liberty formation, unknown in the underlying Waynesville strata. In other words, there is no reason for believing that the rock of which the pebbles are composed is older than that of the formation in which the pebbles now occur. In fact, at several localities along the creek, the rock immediately underlying the pebble-bearing layer is sufficiently similar to the rock forming the pebbles to have given origin to the latter.

These fine-grained pebbles usually do not exceed 6 inches in length, 3 inches in width, and an inch in thickness, but specimens 12 inches long, 7 inches wide, and 2 inches thick are known, and one pebble 18 inches long, 11 inches wide, and 3 inches thick was observed.

2. The second type of pebbles usually consists of a fine-grained blue limestone, in which the grain is distinctly less fine than in the first type. The granular structure usually may be recognized without the assistance of a magnifier. Worm-burrows usually are absent, and no incrusting bryozoans or specimens of *Protarea* have been observed. The color of the rock is bluish gray, similar to that of the inclosing rock, and the outlines of the pebbles may be distinguished from the latter chiefly by the finer grain of the rock forming the pebbles, and usually also by differences in the stratification planes running through the rock. Such fossils as occur in these pebbles suggest the Liberty age of the rock from which the latter were derived, and the source of this rock could have been one of the underlying layers within this formation.

The pebbles of this second type usually are relatively thin and flat. The upper and lower surfaces usually are parallel, the lateral margins often being vertical or rounding only moderately into the upper and lower surfaces. In vertical cross-sections, therefore, the pebbles appear angular at the margins. Angularity frequently characterizes also the lateral outlines, as observed from above. In other words, the pebbles frequently appear broken off from thin layers of limestone, without much rounding. Some of

the pebbles are only 4 inches in length, and only a few exceed 12 inches in length, 7 inches in width, and 1 inch in thickness, but occasionally specimens much larger than this are seen. One

FIG. 5.—Pebble, of natural size, supporting two colonies of *Protarea richmondensis*. From layer D in the Elk Run section, east of Winchester, Ohio.

FIG. 6.—Limestone slab, of one-third natural size, supporting several pebbles; of these the one represented by Fig. 5 is located at *A*, but in an inverted position. From layer D in the Elk Run section, east of Winchester, Ohio.

pebble 38 inches long, 28 inches wide, and 2.5 inches thick was found.

The relative position of the pebble-bearing layers among the ripple-marked limestones along Elk Run may be seen from the following section. Ripple-marked layers occur here at various levels in a section at least 30 feet thick. Owing to the fact that the dip of the rocks is in the same direction as the flow of the stream, several layers disappear below the level of the stream at one point and reappear farther down the stream. This makes the unraveling of the section more or less difficult in places, but the following section, described in descending order, is as nearly correct as may be determined from the present condition of the exposures, which is unusually favorable for this locality.

SECTION ALONG ELK RUN, 1.5 MILES EAST OF WINCHESTER, OHIO

		Ft.	In.
Layer A.	Exposed about 600 feet south of railroad bridge; crest of ripples running N. 47° W. Pebbles few.		
Interval		5	
Layer B.	Crest of ripples running N. 40° W.		
Interval		3	9
Layer C.	Crest of ripples running N. and S.		
Interval			9
Layer D.	Crest of ripples running N. 40° W. This layer is not ripple-marked southeast of the home of Charles Bailey, but here numerous fine-grained pebbles, many supporting growths of *Protarea richmondensis*, occur (Figs. 5, 6).		
Interval		1	
Layer E.	Crest of ripples running from N. 30° W. to N. 25° W.		
Interval			9
Layer F.	Crest of ripples running N. 35° W.		
Interval		1	6
Layer G.	Crest of ripples varying from N. 3° W. to N. 15° W. at the small fall northeast of the home of Charles Bailey. This layer is exposed also immediately north of the road bridge, and between the road bridge and the railroad bridge. It is characterized by angular, flat pebbles, few in number, but sometimes of considerable length and width, considering the small thickness.		
Interval		6	

		Ft.	In.
Layer H.	Crest of ripples running N. 15° W.		
Interval	....	5	
Layer I.	Crest of ripples running N. and S., faintly defined. Near home of E. E. Jamison.		
Interval	....	5	
Layer J.	Poorly defined ripple-marks, at next house on west side of creek.		
Interval	....	1	
Layer K.	Crest of ripples running N. 70° E.		
Interval	....	1	
Layer L.	Crest of ripples running N. 50° E.		

The fine-grained pebbles first described, apparently consisting of a lime mud, supporting incrusting growths of *Protarea*, *Dermatostroma*, and various species of bryozoans, are specially characteristic of layer D. This layer is exposed at several localities along the creek, but the pebbles are common only southeast of the home of Charles Bailey, on the eastern side of the creek. Here the pebbles rest upon the top of the layer or are more or less imbedded in its upper part. This pebble-bearing layer is exposed also farther up stream, about 500 feet north of the road bridge. Here the pebbles vary from 2 to 4 inches in length, and from a quarter to half an inch in thickness. Farther up stream, immediately south of the road bridge, this layer is strongly ripple-marked, the crest of the ripples running N. 40° W. One pebble was noticed here 14 inches long, 7 inches wide, and half an inch thick. Farther north, where the pebbles are abundant, ripple-marks are absent.

The less fine-grained and more angular blue limestone pebbles, described last, occur in layer G. This layer is exposed between the railroad bridge and the road bridge, a short distance northward. The crests of the ripple-marks vary here (Figs. 1, 2) between N. 3° W. and N. 15° W. in direction, and on the average are about 30 inches apart. The following pebbles were noticed here, imbedded within the upper part of the ripple-marked layer, only the upper surface being exposed. In each case the length, width, and thickness of the pebble are given. One pebble, $4 \times 3 \times 0.5$ inch, lay in a trough and sloped gently toward the west. Another, $12 \times 7 \times 0.5$ inch, lay in a trough in a horizontal position. Two pebbles, $4 \times 4 \times 0.25$ inch, lay in a trough and sloped toward the east. Two pebbles,

4 inches in transverse diameter, lay in a trough in a horizontal position. One pebble, $8 \times 5 \times 0.5$ inch, was imbedded on the eastern side of one of the crests, but in a horizontal position. Two pebbles, one on the eastern and one on the western side of the same crest, were in a horizontal position. The steeper side of the ripple-marks lies on the western side of the crests. The same layer is exposed immediately north of the road bridge, with layer D about 3 feet 3 inches farther up.

Layer G is exposed again at the small waterfall northeast of the home of Charles Bailey. The crests of the ripple-marks here run N. 3° W., the crests are about 28 inches apart, and the steeper slope is on the western side. Here the following pebbles were noticed, the dimensions being given in inches: one pebble, $10 \times 7 \times 1$ inch, in a horizontal position, imbedded along the crest of one of the ripples; a pebble, $12 \times 7 \times 1$ inch, in a horizontal position, buried under the western half of a crest; a pebble, $38 \times 28 \times 2.5$ inches, in a horizontal position, imbedded so that its upper surface is on the same level as that of the surrounding rock. The moderately rounded margins are slightly overlapped by the surrounding rock; and the ripple-marks characterizing the latter are clearly defined as far as the margin of the pebble, but are absent, of course, on the surface of the latter.

Layer G is exposed also farther down the stream, northward. Here the crests of the ripples run N. 15° W., both sides of the ripple-marks sloping equally. One pebble, $6 \times 4 \times 1$ inch, was imbedded up to its upper surface within the ripple-marked layer, and an incrusting bryozoan overlapped one margin of the pebble and the adjacent part of the surrounding rock, showing that enough time elapsed before the deposition of the overlying clay bed to admit of the growth of this bryozoan, the thickness of the latter being about 3 or 4 mm.

The pebbles in layer A were few in number. One pebble, $6 \times 4 \times 0.5$ inch, consisted of fine-grained rock, resembling the worm-burrowed layer beneath the ripple-marked limestone. Farther north, nearer the railroad bridge, several additional pebbles, consisting of the same kind of rock, were found. The crests of the ripples run N. 47° W., they are 20–30 inches apart, the inter-

vening troughs are about 2.5 inches deep, and the steeper slope is on the western side.

All of the strata included within the 30-foot section here described belong to the Liberty formation. The lowest layer, L, contains the characteristic fossil *Dinorthis subquadrata*, and *Plectambonites sericea* is so abundant here that it suggests a horizon not far above the base of this formation. The abundance of typical *Strophomena planumbona* throughout the section suggests the lower half of the Liberty. *Strophomena vetusta*, associated with *Dinorthis subquadrata* and *Rhynchotrema capax*, is comparatively rare until the layers immediately overlying layer A are reached, but the general aspect of the rock here still is that of the Liberty formation.

Judging from exposures on Graces Run, a little over a mile west of Harshaville, the highest strata exposing ripple-marks occur at least as far up as within 88 feet of the base of the Brassfield limestone. Pebbles up to $6 \times 4 \times 0.5$ inch in dimension occur at a small fall half-way between this point and the mouth of Martins Run, half a mile southeastward. Several pebbles occur also in the wave-marked layers in the bed of Cherry Fork, immediately west of Harshaville.

The highest ripple-marked horizon along Elk Run, east of Winchester, appears to be about 80 feet below an exposure of Brassfield limestone seen along the railroad, west of the creek.

Pebbles up to $7 \times 4 \times 0.5$ inch in dimension occur also on Treber Run, about a quarter of a mile west of the mouth of the stream, a short distance west of the first crossing of the road following the stream. Here the pebbles occur in large, loose slabs of limestone containing a Liberty fauna, and evidently not transported far. The pebbles consist of small-grained blue limestone, similar to those occurring in layer G in the Elk Run section.

Perhaps the chief reason why the presence of pebbles in these ripple-marked strata has received so little attention is because they are so readily overlooked. By far the larger number of pebbles are horizontal in position, their stratification planes coinciding in direction with those of the inclosing rock. Especially is this true of the larger pebbles, while the smaller pebbles occasionally occur

at distinct angles with the inclosing rock. Moreover, the upper surface of the larger pebbles rarely projects distinctly above the surface of the inclosing rock, but more commonly is about at the same level as the latter. On careless examination, the pebbles appear merely as adhering remnants of the next overlying layer of rock. They are distinguished chiefly by the finer grain of the pebbles, frequently accompanied by a difference in color and by a difference in the character and location of the stratification planes.

There is no evidence that the larger pebbles, a foot or more in diameter, ever were turned over so as to present the lower instead of the upper surface of the original rock stratum. Perhaps this statement could be made with equal accuracy of any pebble 6 inches in width. The largest pebbles, so far found, which give evidence of having been overturned before being imbedded have a width of almost 3 inches, although the length may equal 6 inches. In one of these pebbles, obtained from layer D in Elk Run, a thin growth of *Ceramoporella ohioensis* on one edge of the pebble overlaps both the upper and the lower surface of the latter by fully an inch, and additional growths of the same species occur on the lower surface, the entire width of the pebble being $2\frac{3}{4}$ inches. The incrusting specimens of *Protarea* frequently occur on the upper surface of the pebbles, often several colonies on the same pebble, and these colonies frequently overlap the lateral edges, but never occur on the lower surface of the pebbles.

The size and the angularity of the larger pebbles suggest that they have not been transported very far. The absence of overturning of these larger pebbles also suggests only a short distance of transportation. The very irregular surface features of the very fine-grained pebbles, among which evidences of overturning are more frequent, suggest washed lumps of partly indurated calcareous mud rather than strongly eroded and frequently overturned rock.

Although rock similar to that forming the pebbles frequently occurs immediately below the layer in the upper surface of which the pebbles are imbedded, these ripple-marked layers frequently are continuous over such large areas, as determined from exposures along the lateral branches of streams, as to make the origin of the pebbles from underlying strata more or less doubtful. Especially

is this true in the case of the larger pebbles, which apparently have been transported only short distances.

Moreover, there is no evidence of strong unconformities anywhere in the Richmond series of rocks. At no point has a layer of rock been found to overlap the lateral margins of any of the layers for even a vertical distance of 2 feet. Hence an origin from anything like a cliff or coast or beach seems questionable. At least there is no evidence of the presence of any cliff, coast, or beach sufficiently close to the area in question to have furnished the material for the pebbles.

There was a tendency formerly to regard the presence of ripple-marks as evidence of shallow-water conditions and as suggesting the proximity of shore lines. This found expression in a paper by Joseph F. James on the "Evidences of Beaches in the Cincinnati Group."[1] Here the ripple-marks in the upper part of the Cynthiana formation, at Ludlow and West Covington, Kentucky, opposite Cincinnati, and another set of ripple-marks about 300 feet above low-water mark in the Ohio River, presumably in the upper part of the Eden formation, were interpreted as evidences of the proximity of beaches. As further evidence of shallow-water conditions during the deposition of various parts of the Cincinnati group, the presence of raindrop impressions near the top of the Cincinnati group was cited, but the exact location of the rock bearing these raindrop impressions is not given.

The impression that at least a part of the rocks of the Cincinnati group were deposited in very shallow waters finds expression also in a paper by Nelson W. Perry on "The Cincinnati Rocks; What Has Been Their Physical History?"[2] Here raindrop impressions are cited from the vicinity of Smiley's Dam, $3\frac{1}{2}$ miles southeast of Oxford, but 5 miles distant when approached by the road. The dam is located on Fourmile Creek. The lowest strata exposed belong to the Mount Auburn division of the Maysville formation, and a mile westward the *Dinorthis carleyi* horizon near the middle of the Arnheim bed is exposed at an elevation about 50 feet higher. Careful search by the present writer failed to locate

[1] *Science*, V (1885), 231.

[2] *Am. Geol.*, IV, No. 6 (1889), pp. 326–36.

the presence of raindrop impressions or of any other evidences suggesting deposition under shallow-water conditions.

Perry next calls attention to the exposures at the Ridenour Mill, on Little Fourmile Creek, about 7 miles north-northwest of Oxford, where numerous layers in the upper part of the Waynesville and lower part of the Liberty divisions of the Richmond group are ripple-marked.

Next, Perry cites the presence of mud-cracks from a locality near Moores Hill in Dearborn County, in Indiana, presumably from the Waynesville division of the Richmond group. And, finally, he alludes to the well-known ripple-marks in the upper part of the Cynthiana formation, at Ludlow, Kentucky.

Now, whatever may be the opinion concerning the value of ripple-marks as evidence of shallow-water conditions, there can be no difference of opinion as to the evidence presented by raindrop impressions and mud-cracks. However, the presence of raindrop impressions and of mud-cracks must be fully proved. This the present writer has been unable to do.

Specimens formerly interpreted by him as exhibiting raindrop impressions he now regards as ripple-marked, irregular ripples of short amplitude crossing at various angles, leaving intermediate more or less circular hollows. If anyone has clear evidence of the presence of raindrop impressions in Cincinnatian strata, this evidence should be published, accompanied by clear illustrations.

As regards the presence of mud-cracks, the present writer has seen many occurrences of structures suggesting mud-cracks, but has come to regard their origin from exposure of mud-flats to aerial conditions as extremely doubtful.

When mud exposed to the drying effects of the open air cracks, it not only tends to pull apart at the cracks, but the upper, more rapidly drying part tends to pull away from the part beneath. Frequently the cracked surface becomes sufficiently hardened to remain more or less intact when the next tide proceeds to cover it. This causes the subsequently deposited material to settle in part in the cracks, and frequently the part filling the cracks is sufficiently different to be readily distinguished from the original mud deposit.

In the case of sea deposits, the material filling mud-cracks might include coarser-grained deposits or organic material, either entire or fragmental. Now, it is the very frequency of the supposed mud-cracks with the absence of the concurrent phenomena here indicated which throws doubt on their interpretation. In such "mud-cracks" as have been observed hitherto, the material filling the cracks is essentially the same material as that forming the lateral walls of the crack, and no fossil or fragmental material has ever been found in a position suggesting that it had been dropped into the crack, or had been washed into it.

On the contrary, in many cases it has appeared possible that the cracking could have occurred subsequent to the deposition of the overlying strata, in fact long subsequent to the latter, and may not be due to the drying effects of the air along a seashore, but to shrinkage of strata deposited in much deeper waters. Mud deposits in quiet waters have been known to crack without exposure to the air, although the observed cracks have always been of too small magnitude to suggest mud-cracks. Shrinkage, however, may have occurred also long subsequent to the deposition of the overlying strata, during a period of elevation of the entire mass of marine deposits. The gradual filling of the cracks might have been accomplished by slowly circulating waters while the shrinking material still was comparatively soft. While the method of filling of these cracks may vary in different cases, the possibility of their origin from shrinkage long after the deposition of the strata in which they occur should be considered. If anyone has any evidence of the presence of mud-cracks in Cincinnatian rocks which unquestionably are due to elevation of mud flats above water-level before the deposition of the immediately overlying strata, this evidence should be published in detail.

Until the presence of raindrop impressions and of mud-cracks due to exposure of mud-flats to the open air before the deposition of the overlying strata has been proved unequivocally, it is not so certain that ripple-marks indicate shallow-water conditions. They may have been formed a considerable distance below sea-level, at least sufficiently far not to necessitate the immediate presence of a shore line.

Formerly, pebbles were regarded as unequivocal evidences of the proximity of a shore line, but even these may be formed below water-level. This is true especially of the pebbles found in the Ordovician strata of Ohio, Indiana, and Kentucky, since these usually occur only in ripple-marked layers, or in lateral extensions of these layers. The same causes which gave rise to the ripples may have given rise to the pebbles.

These causes apparently include a more or less rapid flow of water. The ripple-marked layers usually consist of more or less fragmental detrital or organic material, frequently in much greater quantity and of coarser grain than in the immediately overlying and underlying layers, as though freed from the accompanying calcareous and argillaceous muds by repeated rewashings of the materials constituting the ripple-marked layers. These muds either were washed to more distant areas or were, in part, held in suspension in the overlying waters for a short time. The ripple-marked layers frequently show evidences of cross-bedding, especially immediately beneath the crests of the ripples, thus also suggesting current action. The larger pebbles, a foot or more in diameter and only an inch or two in thickness, may easily have been formed by currents dissecting a more or less fine-grained stratum, and leaving remnants of the latter more or less imbedded in the current-washed material farther on. In limestone layers not exceeding four inches in thickness, even directly beneath the crests of the ripples, the larger pebbles scarcely could incline very much. The source of the pebbles readily could have been some formerly existent layer located less than a foot above the present level of the pebble. The finer muds of the intervening section could have been washed away, and the coarser material retained to form the major part of the ripple-marked layer, in the upper surface of which the limestone pebbles are imbedded.

Especial attention should be called to the fact that, even where the ripple-marked layers are most abundant, many of the intermediate limestone layers may show no trace of ripples. Hence, the frequent absence of ripple-marks needs explanation fully as much as their locally more or less frequent presence.

One of the causes giving rise to widespread current-action may have been violent and widespread storms. Considering the fact that the Cincinnatian strata were deposited in epicontinental seas, storms easily, at times, might have blown vast quantities of water over those parts usually covered only by shallow waters. Such storms occasionally are experienced on the Gulf coast, and along the coast of the southern Atlantic states. The ebb flow of these accumulated waters, after the storm, might easily give rise to widespread ripple-marking of the last deposited strata, even at a considerable distance from actual shore lines. Such an origin of currents would predicate wide areas of gradually shallowing seas over which the surface waters blown before the wind would tend to accumulate. Currents due to such causes might be expected more readily in the comparatively shallow waters of epicontinental seas than along the more abrupt shores of the deeper oceanic basins.

The presence of numerous well-preserved colonies of *Protarea* and of delicate growths of *Stomatopora* and other bryozoans on the upper surface of the pebbles at the Elk Run locality, east of Winchester, Ohio, is indicative of submerged conditions at least immediately after the formation of the pebbles. In a similar manner, the long crinoid columns found on the surface of the ripple-marked layers of lower Trenton limestone, at Hull, in Canada,[1] indicate that fairly deep waters were present immediately after the formation of the ripple-marks, and may have been present even during their formation.

Ripple-marks comparable in dimension with those characteristic of the Ordovician limestones of Ohio, Indiana, and Kentucky are not unknown along our present shores. They occur where waters accumulating in extensive salt marshes or in estuaries during high tide find a ready outflow to the sea during ebb conditions. In these cases the steeper slopes of the ripple-marks are directed away from the shallower waters.

It is remarkable, however, in the case of the ripple-marks on the Ordovician limestones of the areas here under discussion, how

[1] Kindle, *Jour. Geol.*, XXII (1914), 712.

slightly the slopes on the two sides of the crests of the latter differ in most cases. Frequently it is difficult to determine a difference in slope at all, and rarely is this difference strongly defined, as in the case of the strong ripples found after ebb tide along our present coasts.

Eventually it may be possible to accumulate sufficient evidence to determine with considerable certainty the conditions under which many of the strata of ancient days were deposited. To many the evidence appears to be already at hand. To others a revision of the evidence may appear necessary. To the writer it appears desirable that those who have indubitable evidence of land conditions during the deposition of Ordovician strata in the states of the Ohio Valley should publish the same. This is true especially in case of raindrop impressions and of mud-cracks, which are favorite evidences locally of shore and land conditions during Ordovician times.

REVIEWS

Upper White River District, Yukon. By D. D. CAIRNES. Geol. Survey Canada, Memoir 50, 1915. Pp. 191, figs. 2, pls. 17, maps 3.

This report covers an area of about 800 square miles lying along the Alaska-Yukon International Boundary from latitude 61° 40′ to 62° 30′. It is considered to be a promising area for mineral deposits of economic value.

The oldest rocks exposed are mica schists referred to the Yukon group of pre-Cambrian age. Upon these rest 1,500 feet of Carboniferous limestones and clastics followed by 1,000 feet of Mesozoic shales and sandstones. At a few points Tertiary beds were observed. These beds are in part flat-lying, and in part have been highly dynamically metamorphosed.

The writer believes that the Nutzotin Mountains are due to differential erosion rather than to faulting. They remained as a region of considerable relief at the time of the peneplanation of the Yukon plateau region and were further uplifted between the late Miocene and the early Pleistocene. A different explanation from that suggested by geologists of the United States Geological Survey is advanced to account for drainage changes along White River.

W. B. W.

Wyoming and McDowell Counties. By R. V. HENNEN. West Virginia Geol. Survey, 1915. Pp. 783, pls. 31, figs. 28, maps 2.

McDowell County, situated on the southern border of the state, has led all the counties in the state in coal production since 1905. Approximately 15,000,000 tons were produced in 1915, and at this rate its available coal will last about two hundred and fifty years. Wyoming County coal fields have not been developed until recently, but its coal reserves equal those of McDowell County.

The Pottsville series has a remarkable development here. It increases from a thickness of 250 feet at the northern edge of the state to a maximum of 3,850 feet in these counties. It has been differentiated into three groups and two score formations.

A new feature in this report is a series of 25 maps of these counties showing the minable coal areas of as many different coal horizons. Under separate cover are topographic and geologic and structure contour maps.

W. B. W.

Oil and Gas Fields of Ontario and Quebec. By WYATT MALCOLM. Geol. Survey Canada, Memoir 81, 1915. Pp. 248.

This memoir has been prepared chiefly for those interested in the commercial development of oil and gas. It treats of the lithology, stratigraphic relations, and areal distribution of the geologic formations from the Potsdam to the Chemung. The predominant structural feature is a gentle dipping of the strata to the southwest away from the pre-Cambrian axis. The northeastern extension of the Cincinnati anticline reaches into Ontario.

The productive horizons are not limited to one formation. Gas is found in the Medina, oil and gas in the Guelph and Salina, and oil in the Onondaga. The production of gas has increased steadily, but the oil output reached a maximum in 1907, and since then has fallen greatly.

Analyses of gas from different fields show a surprising uniformity of composition. The writer of the report believes this to be incompatible with a local and separate origin of the gas for each field.

W. B. W.

Arisaig-Antigonish District, Nova Scotia. By M. Y. WILLIAMS. Geol. Survey Canada, Memoir 60, 1914. Pp. 173, maps 2.

The chief interest in this memoir lies in its contribution to stratigraphy. Careful attention had been given already to the region, for in it lies the key to the stratigraphy of a considerable area. The purpose of this investigation was to work out in still greater detail the sedimentary record and the ages and relations of the igneous rocks.

Of the Paleozoic systems, the Cambrian and Permian are missing. Where possible, correlations are made with the type sections of Europe. Separate chapters are reserved for structural and historical geology. Igneous geology is given the same careful attention as the sediments. The igneous rocks are limited largely to acid and basic intrusives in the Ordovician, and to intrusive diabase sheets in the Mississippian.

W. B. W.

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LABIDOSAURUS[1] COPE, A LOWER PERMIAN COTYLOSAUR REPTILE FROM TEXAS

SAMUEL W. WILLISTON
University of Chicago

Although remains of the genus *Labidosaurus* are not rare in the upper Clear Fork beds of Texas, it has only been lately that fairly complete skeletons have been secured. During the past season Mr. Paul C. Miller was fortunate in finding, not far from the paleontologically famous Craddock Ranch, near Seymour, Texas, some half-dozen specimens, associated in a spot but a few square yards in area—specimens which furnish nearly every detail of the skeletal structure, excepting, as usual, the length of the tail. These specimens come from a horizon that I have several times mentioned, that from which the connected skeletons of *Seymouria* and *Trimerorhachis*, previously described, were obtained. Like those, these skeletons were inclosed in hard clay nodules of a mottled red and white color. The bones are rather soft and white in color, while the matrix is very hard, making their preparation difficult.

[1] *Labidosaurus* Cope, *Proc. Amer. Phil. Soc.*, 1896, p. 185; Case, *Zoöl. Bull.*, II (1899), 231 (*Pariotichus*); *Revision of the Cotylosauria* (1911), 45, 101; *Permocarboniferous Beds of North America, and Their Vertebrate Fauna*, p. 137, 1915; Broili, *Paleontographica*, XI (1905), 51; Williston, *Jour. Geol.*, XVI (1908), 359; *ibid.*, XXII (1914), 65; *ibid.*, XXII (1914), 414; *Contributions from Walker Museum*, I, No. 8 (1914), 157; *ibid.*, No. 9 (1916), 221; Branson, *Jour. Geol.*, XIX (1911), 136; v. Huene, *Bull. Amer. Mus. Nat. Hist.*, XXXII (1913), 351.

The most important of these specimens (No. 174 Fig. 1), that upon which the restoration (Fig. 8) chiefly is based, includes the right half of the skull, the connected series of vertebrae and ribs to the base of the tail, the pectoral girdle, the humerus, the radius, the ulna, a single metacarpal, the pelvis, seen from below, and the right hind leg complete, except the phalanges of the fourth and fifth toes. Another specimen (No. 177) comprises the skull, a

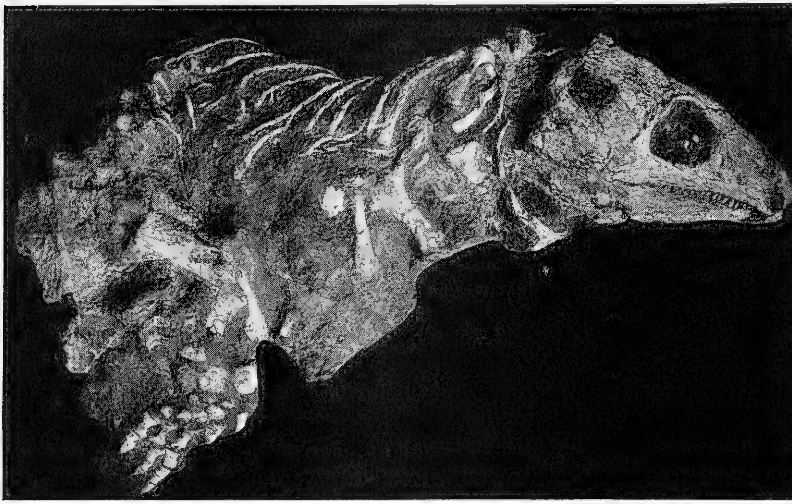


FIG. 1.—*Labidosaurus.* Specimen No. 174, as prepared. One-fourth natural size.

complete series of closely articulated vertebrae and ribs to the second sacral, the clavicular girdle in place, a part visible of the left scapula, the left front leg, with the exception of most of the phalanges, a femur, and part of the pelvis. This specimen has been laid bare on the ventral side. A third specimen (No. 176) has the skull with its upper part largely destroyed, the series of vertebrae and ribs nearly to the sacrum, the pectoral girdle, both humeri, one forearm, and part of the hand. The fourth specimen (No. 178) comprises a complete skull, the connected vertebrae to about the middle of the back, and the connected pectoral girdle. The other specimens are more fragmentary and have not yet been prepared.

In addition to these specimens preserved in their matrix, there are eight other more or less complete skulls, as many more incomplete, and numerous series of vertebrae, girdles, and limb bones—altogether about thirty specimens. The material, it will be seen, is ample to determine the skeletal structure.

In size, these specimens vary not a little. About half of them are of nearly uniform size, the skull measuring seven inches along the median line; these clearly all belong to the type species *L. hamatus* Cope. Four other skulls, including the one originally described by Case and myself as *Labidosaurus* (*Pariotichus*) *incisivus* (No. 634) and Nos. 174 and 178 measure five inches along the midline. All of these, unless it be No. 634, come from the upper Clear Fork horizon. Two other skulls, and parts of others, including the maxillae in which the additional maxillary teeth were observed, are of smaller size, measuring only four inches. Two of these (180 and 183) come from a much lower horizon, that which has yielded most, if not all, the known specimens of *Pantylus*. They have but a single row of teeth in the mandibles, and have the long premaxillary teeth, and cannot be placed in the genus *Captorhinus*, though they differ materially from the large skulls in having the face less compressed. Probably they will eventually find a place in another yet unnamed genus. The most important of these is a very perfect specimen (No. 183) herewith figured (Fig. 2). In each orbit there is preserved a part of a sclerotic ring, the earliest appearance, I believe, of such ossifications in a reptile. The separate plates (Fig. 3) are narrow, with a flattened, thumblike projection on each extending over the adjoining plate near its inner end; otherwise they are not imbricated. In specimen No. 174 fragments of similar plates are preserved in the orbit. Doubtless all the members of this group had similar ossifications of the sclera, and it is not at all improbable that most Paleozoic reptiles possessed them.

Skull.—Nearly every detail of the skull of *Labidosaurus* is known with assurance, owing to the combined researches of Cope, Broili, Case, and myself. In the first figure of the skull given by me, the quadratojugal was given as a distinct bone, and also a division of the squamosal into two bones. In my second figure the quadratojugal was omitted as doubtful, as was also the supratemporal. I

thought that I found in two specimens a suture separating the posterior part of the squamosal, and recognized it as the "epiotic," following Cope. A skull acquired very soon thereafter showed clearly that there was no such suture, and that the ascription of a tabular was an error, as recorded by Branson (*op. cit.*). The sutures given in the present figures have been corroborated in at least a dozen skulls, and there can no longer be any doubt about

FIG. 2.—*Labidosaurus*(?). Skull, from the side. Three-fourths natural size. No. 183.

them. The figure given by v. Huene (*op. cit.*), I regret to say, has a number of inaccuracies. There is a distinct quadrotojugal, a bone found in nearly all the American Permocarboniferous reptiles; there is no supratemporal, absent also in *Procolophon* and *Captorhinus;* and no tabular, present in all other cotylosaurs, and in many theromorphs. Of the structure of the under side of the skull I have no corrections to make of my earlier figures. In none of the large specimens is there a trace of the parasphenoid; it is certainly absent in some; in two of the smaller skulls it is present though small. Perhaps its absence is a generic or a specific character. Nor have I any changes to make in my figures of the

occipital region. The paroccipital exists as a distinct bone. The proötic, epipterygoid, and the relations of the quadrate are as I have described and figured them. The small bones above the brain case, which I doubtfully called the "alisphenoids," in the doubt now existing as to the presence of the mammalian alisphenoid in the reptiles may be called the "postoptics," the name first proposed for them by Cope. Nor have I any emendations to make of the structure of the mandible as figured by me.

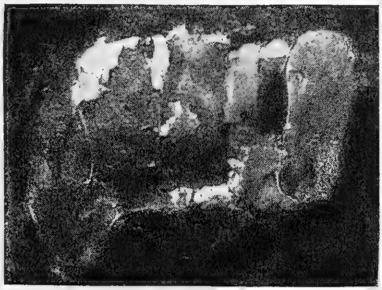


FIG. 3.—*Labidosaurus.* Sclerotic plates. Enlarged.

Whether all the forms have additional teeth on the inner side of the maxillae posteriorly I cannot say since in most specimens the mandibles are tightly closed, precluding an examination of this region. Two smaller maxillae, as recorded by Branson, possess them. The premaxilla has, in most specimens, three teeth, of which the first is the largest, and the third small. Case has based a species, *L. broilii*, on the presence of two elongated premaxillary teeth, but I think that the character is variable. The number of teeth in the maxilla also is variable. In the earlier specimens I could find not more than seventeen or eighteen. In that herewith figured (No. 174) there are twenty-four, the posterior ones quite small. Whether this difference is a specific or an individual character I am not prepared to say. I am unwilling to give specific names until I am assured that I know specific characters, and such we do not know well in any genus from the American Permian—in general I am skeptical of the "species" of all fossil reptiles.

Nearly every skull of *Labidosaurus* hitherto found was fossilized in a horizontal position and it has been exceedingly difficult to determine the amount of depression they had suffered. Among the numerous skulls now at my command there are two only which have not thus been distorted. One, an unusually large skull measuring eight inches in length, shows very little if any distortion. The other, that herewith figured (Fig. 1), had been evenly split along the

median line and the right half has been preserved in articulation with the vertebrae lying upon its side. In this specimen, the slight distortion is in the other direction; its height posteriorly is a little too great. From a study of all these specimens, however, one can determine almost exactly the elevation of the posterior part of the skull, about as I have figured it in the restoration. Whence it follows that in all the figures hitherto given, including my own, the skull is shown too much flattened posteriorly, and the orbits too

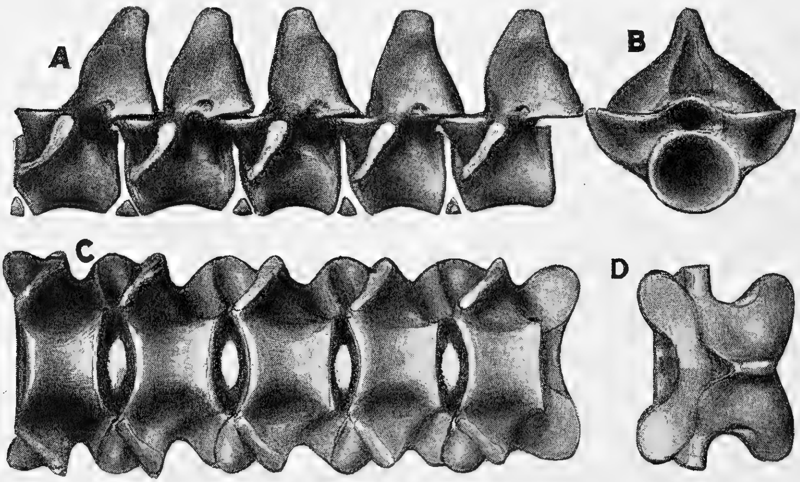


FIG. 4.—*Labidosaurus.* Anterior dorsal vertebrae. *A*, from the side; *B*, from in front; *C*, from below; *D*, from above. Natural size.

ovate in form when seen from the side. In reality the orbits seen from the side are almost circular in outline.

Vertebrae.—The peculiar structure of the vertebrae, which *Labidosaurus* shares for the most part with *Captorhinus*, has been described sufficiently well by Case, and will be seen from the accompanying figure (Fig. 4). Vertebrae of this type are known exclusively from the Texas deposits, with one exception, a specimen of a large form found by Professor Case in the El Cobre Cañon. I believe that when the skull of this genus is discovered it will prove to be of the *Labidosaurus* type. I may add that the horizon of this specimen is rather high up in the Cobre deposits.

The atlas cannot be made out in any of the connected specimens. Doubtless there is also a proatlas. The axis scarcely differs from the following vertebrae. There are twenty-five presacral vertebrae, definitely shown in specimen No. 177. This is the number found by Case in *Captorhinus*, and one less than the number in *Limnoscelis*, a genus which has not a few points of resemblance to *Labidosaurus*. It is two more than is possessed by *Seymouria*, and three or four more than in *Diadectes*. In *Pantylus* the number is unknown.

The postaxial, presacral vertebrae are scarcely distinguishable from each other, except the five posterior ones, which have no processes for rib articulation. The spines anteriorly are a little more slender, giving greater freedom of vertical movement. The transverse processes anteriorly are a little longer, standing out beyond the margin of the zygapophyses; they are also a little stouter here, extending down farther on the sides of the centrum. The intercentra anteriorly are small, not nearly filling out the space between the margins of the centra. There are two sacral vertebrae; the first bears a stout rib, with a broad, vertical face, as long as the centrum, for articulation with the ilium; the second has a much smaller rib, only touching the ilium behind and below the first rib. The caudal vertebrae, so far as known, are narrower than the presacral, and have more slender processes. Their ribs are co-ossified with the centra, unlike those of *Seymouria*.

The first and second ribs are slender; the third is broader and much longer. The fourth, as in *Captorhinus*, is remarkable (Fig. 1) and would hardly be recognized as a rib if found isolated. Its length is less than three times the width of the distal end. It is narrowed in the middle and much expanded at its extremities. Like the early ribs of *Seymouria*, *Diadectes*, and *Limnoscelis*, its function was the support of the scapula.

Pectoral girdle (Figs. 5, 6).—In five different specimens, the pectoral girdle, more or less complete, is found in position with the skull and but slightly dislocated from its association with the vertebral column. In each case the front end of the interclavicle with its articulated clavicles lies between the angles of the jaws and immediately under the occipital condyle—precisely its posi-

tion in the temnospondylous amphibians and in *Diplocaulus*. There was literally no neck in the cotylosaurs. In three of these specimens the shaft of the clavicles is turned dorsad at a right angle to the lower, horizontal, and expanded part; in two or three others the angle is slightly greater. In one specimen, that shown in Fig. 1, lying in immediate connection with the upper end of the

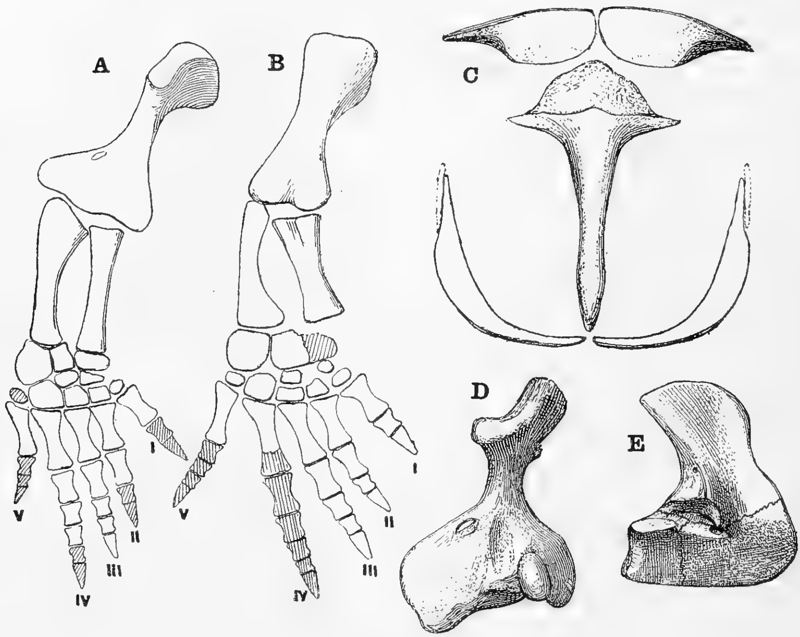


FIG. 5.—*Labidosaurus*. *A*, front leg; *B*, hind leg; *C*, clavicular girdle clavicles from below, interclavicle from below, clavicles from in front; *D*, humerus ventral face; *E*, scapula, outer face (No. 634). All figures about one-half natural size.

clavicle, there is a very slender bone about 20 mm. in length; a similar bone is also found in specimen No. 178 with quite the same relations. There would seem to be little doubt that it is a vestigial cleithrum. In *Limnoscelis* the cleithrum is very small, though much larger in *Diadectes*. None has been observed in *Seymouria*, but I am inclined to believe that all the American cotylosaurs possessed the element, though in some cases it was vestigial. The scapula figured (Fig. 5, *E*), is quite complete, but is lying on its

side and has suffered a lateral compression. In specimen No. 178 (Fig. 6) the scapulae lie almost perfectly in position with the clavicular girdle, or at least that of the left side. The blade may have been pressed outwardly a little, but the angle between it and the horizontal coracoids is nearly rectangular. As a whole, the scapula is rather broad and short, as in *Limnoscelis*, a little narrower in the larger specimen. The sutures separating the coracoids and the scapula have been corroborated in several specimens.

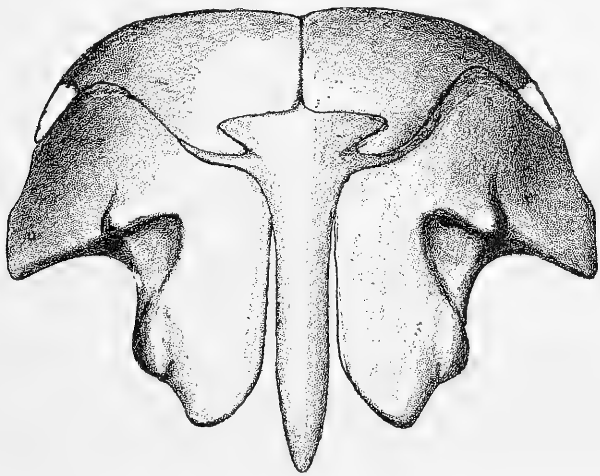


FIG. 6.—*Labidosaurus*. No. 178. Pectoral girdle, from below. One-half natural size.

Forelegs.—The humeri of the different specimens vary appreciably in shape, but I do not know the value of the differences. They have a greatly expanded distal end, as would be called for by the large and stout hand. The radius and ulna are shown connected in three specimens. They are somewhat more slender than the posterior epipodials, and are much shorter than the humerus.

The carpus was correctly figured by me in my earliest paper; unfortunately some of the bones were incorrectly identified: it is the fifth and not the first digit which was missing. There are definitely four phalanges in the third finger, and there can be little, if any, doubt that the formula was the primitive one of 2, 3, 4, 5, 3. The fifth carpale I have not recognized, but it doubtless was ossified.

Pelvis.—Of the pelvis the ilium is not visible in its entirety in any specimen. In the restoration I have borrowed from Broili's figure the outline of the upper part articulating with the sacral ribs. The flat, platelike pubes and ischia are firmly united in the middle, with no opening except the usual obturator foramen; they are proportionally long.

Hind legs.—The femur has been well figured by Case. It is rather short and stout, much stouter than in *Captorhinus*. The tibia is unusually stout, and the fibula is much curved; both bones are much shorter than the femur. My original figure of the tarsus was erroneous in several particulars, as was suggested by Jaekel. Most of the tarsal bones have been correctly figured by Case. In one specimen (No. 174) I find what I believe to be evidence of two centralia, as in *Ophiacodon*, though Case figures but one. The phalangeal formula was doubtless 2, 3, 4, 5, 4. The first three digits are shown in the figure (Fig. 1). The first digit of both the hand and the foot is relatively large, and its metapodial was capable of but little divarication from the others. The fifth metapodial was but little shorter than the fourth.

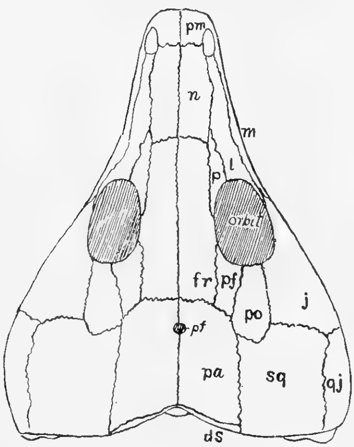


FIG. 7.—*Labidosaurus*. Outline of skull, from above: *pm*, premaxilla; *n*, nasal; *m*, maxilla; *l*, lacrimal; *p*, prefrontal; *fr*, frontal; *pf*, postfrontal; *po*, postorbital; *j*, jugal; *pa*, parietal; *sq*, squamosal; *ds*, dermosupraoccipital; *pf*, parietal foramen. (Engraving from *Water Reptiles*, p. 22, Fig. 6.)

Parenthetically I may add that I do not at all agree with Goodrich[1] in imputing to the form and position of the fifth toe so much importance in the classification and phylogeny of the reptiles. The divarication and hook shape of the fifth metatarsal have been due, I believe, to modifications of the tarsus and doubtless have arisen homoplastically in various lines of descent. In all primitive reptiles there was a fifth tarsale. As has been amply proved, I

[1] *Proc. Royal Soc.*, LXXXIX (1916), 261.

think, the bone has absolutely disappeared in all modern amniotes, leaving a space that was soon occupied by the proximal end of the fifth metatarsal, which came to articulate directly with the large fourth tarsale. In many Permian reptiles a divarication and proximal elongation of the fifth metatarsal had begun. This change in the articulation, it seems to me, will easily account for the change in the form of the fifth metatarsal in crawling plantigrade reptiles. In the rectigrade, and more ambulatory reptiles, on the other hand, with less functional use of the fifth toe, the metatarsal retained more of its primitive shape and position parallel with the fourth, especially in the forms ancestral to the mammals.

The chief fallacy in Goodrich's arguments lies in deriving the stegocrotaphous chelonian skull from a single- or double-arched ancestor because of the shape of the fifth metatarsal. It is now conceded that the turtles must have had a direct ancestry from the cotylosaurian type of reptile; if so the hook-shaped metatarsal must have been an independent acquirement.

The hands and feet of *Labidosaurus* (Fig. 5) are relatively large and powerful, the foot nearly as long as the leg, the hand as the arm. The first digit of each is relatively large and but little divaricated in life; its

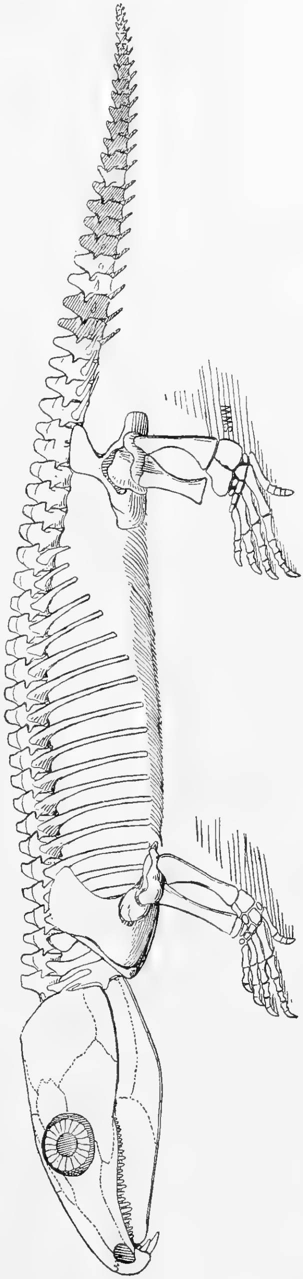


Fig. 8.—*Labidosaurus*. Skeleton. About one-fourth natural size

metapodial is but little smaller than the second. The metapodials are all stout, but the digits are short, tapering rapidly. The ungual phalanges are more pointed than in either *Limnoscelis* or *Diadectes;* the fifth tarsale, as usual, is small.

Very slender ventral ribs, for the first time recognized in this genus among the cotylosaurs, are present in numerous specimens. So far as they are preserved, they do not seem to differ from those of *Ophiacodon* or *Varanops*, for instance. It is pretty certain that they are absent in the diadectids and *Limnoscelis*. Why some genera in each order of reptiles should have retained these bones, while others lost them, I am not prepared to hazard a guess. Possibly they have something to do with water habits.

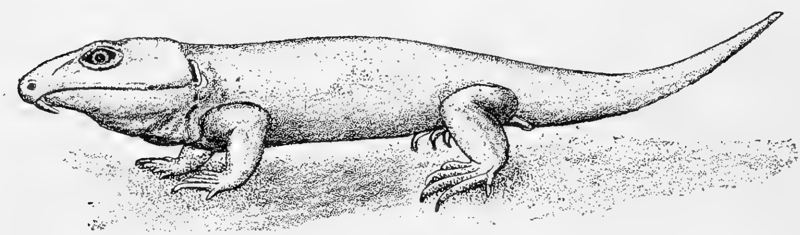


Fig. 9.—*Labidosaurus*. Life restoration, about one-eighth natural size

Restoration (Figs. 8 and 9).—The only attempt that has hitherto been made at the restoration of the skeleton of *Labidosaurus* is that of Broili, which was quite acceptable, considering our little knowledge of the genus and its allies at the time he made it. That he placed the front legs so far back as he did, is not surprising; almost anyone would have done likewise at the time; and in the curvature of the vertebral column he was unduly influenced by the erroneous early restorations of *Pareiasaurus*, at that time supposed to be a near relative. I may only remark here that the present restoration, based as it is upon so much material, has scarcely anything conjectural about it, or anything that has not been corroborated by several specimens. As usual, the length of the tail is still in doubt. I have assumed that it was about as long as in the allied captorhinids, of which we know the tail more definitely.

Habits.—Granted a fairly complete knowledge of the osseous structure of such early reptiles, there must remain more or less

conjecture as to how and where the creatures lived. The two striking characters seen in the skeleton are the elongated, hooklike incisor teeth and the very powerful feet. Were they correlated? I believe that they were. There is no evidence that the powerful feet were developed for use in swimming, though doubtless the creatures swam well. Nor is there any evidence that the creatures used them for digging holes in which to crawl, for the very good reason that the front legs were altogether too short; they could not have scratched their own noses, much less dig holes for the body to enter. Why not then assume that the feet were developed for digging for food? The epipodials are relatively short, a character constantly found in animals using their legs for propulsion in the water. But why not the same shortening to give greater immediate power in digging? I believe, then, that *Labidosaurus* lived about the lowlands, on the borders of the seas or lakes, and found its livelihood in extricating worms and larvae from the rocks or soil, for which the long, hooklike front teeth were admirably fitted. The posterior teeth in *Labidosaurus* were not strictly carnivorous; they were better adapted for cutting than for tearing or seizing. They are flattened, with an obtusely pointed apex; and the palatine teeth were very small, except those of the "transpalatine" part of the pterygoids. The motion of the head upon the shoulders was limited laterally, rather free vertically. The trunk was not very flexible. The spines were short, but the great development of the arches of the vertebrae furnished ample place for the attachment of muscles controlling the head. Finally, in motion the animal must have been slow and sluggish.

In some respects *Labidosaurus* is the most specialized of all the American cotylosaurs, especially in the loss of the supratemporal and tabular bones, rarely absent in other cotylosaurs; and in the reduction of the dermosupraoccipitals, and their restriction to the occipital surface of the skull. The genus could not have been ancestral to any known later cotylosaurs, though possibly the Captorhinidae may have been allied to the ancestral stock of the Procolophonia of the Trias.

NOTES ON THE 1916 ERUPTION OF MAUNA LOA

HARRY O. WOOD
Hawaiian Volcano Observatory

The writer's observations and comments on this eruption divide naturally into four parts:

I. Distant observation and photographic record of the outbursts of fumes on May 19, and of the beginning of flow on May 21–22, 1916.

II. Observation at the front of the Honomalino branch of flow on May 23.

III. A hurried reconnaissance of the Kahuku branch of flow, and of the flow-source region, on May 30–31.

IV. A thorough examination and photographic record of conditions throughout the region of the source of flow, made in the company of Dr. A. L. Day, in the six days, June 28—July 3, 1916.

Treatment under these headings makes for a somewhat extended and rambling account; but it has been found very difficult to present the complicated sequence of observations, which in some respects are unrelated, in any more succinct way.

I[1]

The beginnings of this eruption were noticed first in the early morning hours of May 19, 1916. No immediate premonitory symptoms were recognized previously. The earliest observations which have come to notice were made by Captain D. F. Nicholson, of the steamship "Hamakua," and by Mrs. R. A. McWayne, of Papa.

At about 3:45 in the morning, while sitting on the bridge as the "Hamakua" was steaming around South Point, Captain Nicholson experienced an earthquake. The sea was smooth and

[1] Much of the matter in Part I was published at once in the *Weekly Bulletin* of the Hawaiian Volcano Observatory, IV, No. 5, pp. 34–37; but this report was necessarily fragmentary, and partly erroneous, so it is restated here.

the weather calm and cloudless. Suddenly the ship trembled from stem to stern, as though it had grounded on a beach, and loose things in the ship's galley were disturbed; also the smooth sea surface suddenly became agitated violently by the commingling of several different systems of waves, an action which kept it in a state of turmoil for about a minute. (No shock so strong as this one was recognizably registered in the Whitney Laboratory of Seismology at Kilauea.)

A little later, at about 4:15 A.M., Captain Nicholson heard a sound lasting for about three seconds, which he likened to a volley of musketry, and he then saw what he described as a spiral column of fumes rising from a point high up on the south flank of the mountain. From her residence above the road near Papa, Mrs. McWayne in the early morning hours saw a bright glow high up the mountain.

During the morning and forenoon hours of May 19 a swarm of local earthquakes was registered at the Whitney Laboratory. All these were extremely feeble shocks, even when considered from the seismographic point of view. The earliest of them was recorded a little before three in the morning. Beginning in the late forenoon a lull followed, less than twenty-four hours in duration.

Throughout the evening and night of May 18, and the morning and forenoon of May 19, the weather was brilliantly clear. Looking westward from the Hawaiian Volcano Observatory, situated on the northeast margin of the crater of Kilauea, one could see nearly the whole profile of Mauna Loa outlined sharply against the sky. From late evening until dawn there was brilliant moonlight. Until midnight, and at 6:15 A.M., no signs of eruption were seen from the vicinity of the observatory. However, at about 6:15 A.M. the beginning of a fresh outburst of fumes, high on the mountain slope, was seen by Captain Nicholson, whose ship had then come to anchor at Honuapo.

At about 7 A.M., perhaps a little before, a definite outbreak and uprush of fumes became visible at Kilauea. At first a group of cloud-forms appeared high up on the south flank of Loa, rising from behind the mountain profile at a distance of at least twenty-five miles, as viewed from near the observatory. Here these were

first seen by Joseph Moniz. Though their appearance and development exhibited peculiarities, Moniz at first thought them to be ordinary cumulus clouds, such as frequently rise from behind the mountain. Yet they held his attention. After about ten minutes, since they continued to rise straight upward at the same place, he pointed them out to others; but still there was doubt as to their character, and he allowed more than a half-hour to pass by before he called the attention of the writer to them, at about 7:35 A.M., having grown surer that they were columns of fumes.

When first seen by the writer there were two chief standing columns in which fumes were swirling rapidly straight upward and merging in a double cumulus crown. The column higher up the slope was somewhat larger and taller than that lower down; and these were then separated by a clear interval whose width was about the same as the diameter of the larger column—about 1,000 feet. As soon as possible the writer began making a series of photographic records of this action, illustrating its development throughout the rest of its duration.[1] Five of these are shown here, Plate II, *a*, *b*, *c*, *d*; Plate III, *a*. The life of this outbreak was short.

The higher fume column then rose above the mountain profile probably from 11,000 to 12,000 feet, and the lower from 8,000 to 10,000 feet. Very quickly other subordinate columns appeared, first at both sides and then in between the chief ones, and soon all had merged into a single pillar of uprushing fumes, issuing more and more copiously and rising to higher and higher altitudes. By 7:45 (Plate II, *a*) the diameter of this column had thus increased to more than a mile, where a little earlier the total width including the clear space did not exceed 3,000 feet. The column had now reached a height of 15,000–18,000 feet above the mountain profile. Its stem resembled a huge column fluted with drapery hung in simple vertical folds. The cumulus crown still showed a double head, and thus continued to indicate the positions of the two dominant fume columns which, in reality, persisted throughout

[1] These views—12 (14) in all—were made on Wratten Panchromatic M plates, quarter-plate size, through a K_3 filter and a Zeiss Double Protar lens, F=13 cm., with a stop of *f*45. Time exposures of about five seconds were made with the earlier views; but, with increasing actinicity, the later exposures were clipped a little short.

the outbreak. Also a smoke ring is shown encircling the upper part of the column below the crown. By eye observation the writer did not notice this ring until about 7:50 A.M. Despite this he feels confident that it had not begun to form when he first saw the eruption cloud.

After 7:50 A.M. the form of the eruption cloud underwent rapid changes as the continued emanation of fumes added to its bulk, and convection currents and varying winds at different altitudes continually reshaped it. At 8:00 A.M. the diameter of the stem had increased to from $1\frac{1}{2}$ to $1\frac{3}{4}$ miles and the smoke ring, which had rapidly enlarged, had begun to fray and spread horizontally about equally in all directions, except for a slight elongation toward the northwest, forming the striking mushroom shown in Plate II, *b*. By this time the crown had reached a height of 20,000 feet, or more, above the mountain profile, and its tip was just beginning to fray in the upper wind.

At a little after 8:00 A.M. the uprush of fumes began to dimish, and by 8:30 the two dominant columns were again separated, and the subordinate columns had ceased to rise continuously. The fume cloud had spread rapidly at the level of the smoke ring, forming a cloud blanket, and this, with the fraying and drift to eastward from the summit of the crown, gave rise to the beautiful cloud-form shown in Plate II, *c*. This has been likened aptly to a ballet dancer. The emanation of fumes continued to diminish rapidly, as is emphasized in the view (Plate II, *d*) taken at 9:05 A.M. Only a graceful cloud-form then remained, with thin columns of rising fumes.

By 10 A.M. (Plate III, *a*) it required keen observation to detect any further output of fumes; and by 10:30 this could be made out only by experienced eyes. By 11:00 A.M. the action was doubtful, and it grew more and more doubtful afterward—though cloud-forms occasionally appeared where undoubted fume columns had been rising. By noon nothing could be seen but a frayed stratum of high cloud overspreading the sky above the mountain. This exhibited ripple-marking, like cross-waved cirrus. It persisted until after sunset.

From about 8:30 A.M. on, short-lived, subordinate columns, wisplike in appearance, were noted at points a little higher up the slope than previously and at points much farther down the slope also, over a span from five to seven times as great as the width of the fume column at its greatest. These lateral columns did not persist individually, and gradually they ceased to appear.

Until the smoke began to fray and spread out like a blanket, the columns of upcurling fumes were fleecy white in appearance in the bright morning sun, with cream tints also, like cumulus cloud; and so too was the cumulus crown. As the blanket spread, however, it shadowed first the column and then its own lower surface, so that these shaded portions took on a faint, graduated coloring in which brownish and purplish tones of a faded-out quality were commingled with various shades of gray. This coloration developed quickly with the horizontal outspread of the fumes. No truly dark-colored fumes were seen.

After the cumulus crown had risen into the upper air and had begun to fray and drift eastward, such action continued until the lessened emanation of the fumes brought it to an end, late in the forenoon. Altogether, however, only a small percentage of the fumes reached the uppermost levels. Most of the drift was to the northwestward. By 8:00 A.M. this tendency for the horizontal fume-cloud blanket to draw out in the northwest direction was noted. By 9:30 the drift in this direction of the blanket as a whole had become noticeable, and by 10:30 such shifting was marked. This spreading and drift of the cloud blanket to the west and northwest until it stretched out back of the mountain profile, so as to extend below the skyline, made a cloud-colored background against which were rising the cloud-colored fumes, slightly tinted with brown. This made the fuming very hard to see, but there is no doubt of its rapid and progressive diminution after 8:00 A.M. During the afternoon no rising fumes were seen definitely. But for a very short time, just at sunset and after, very thin, translucent fumes were seen, brown in the transmitted light of the western sky.

In the early evening there was cloud and mist intermittent with brief, clear glimpses. From the observatory no definite glow could be seen, but there appeared to be a very faint radiation of

light over the dark sky from a point on the slope near the place of outbreak, though apparently a little lower down. That this emanated from the eruption was, and is, doubtful. It was too faint to be a positive illumination. However, it is the understanding of the writer that a faint glow was seen that night by Captain Nicholson when off Fisherman Point. This and subsequent events strengthen the probability that the faint light seen from the observatory was, in reality, from the eruption.

From the observatory no fumes were seen on the 20th, nor early on the 21st. From Kealakeakua, however, a "pillar of smoke" was seen early in the morning of the 20th by Miss Paris, a lifelong resident of Hawaii, familiar with the appearance of the mountain profile and with the characteristics of eruption here. This appeared high up on the south slope as seen from Kona. From the observatory, just at sunset in the evening of the 21st, thin brown-toned fumes were seen by transmitted light rising from near the place of outbreak. They appeared somewhat more pronounced, even, than on the evening of the 19th.

A small amount of lava probably was ejected at the time of this outbreak. This was reported as seen by men high on the slopes back of Naalehu and Kahuku, and in Kona, but the action was quickly over.

As mentioned earlier, the swarm of earthquakes which preceded and accompanied the first uprush of fumes was followed by a lull in the registration of shocks, of less than twenty-four hours' duration. After this they began to register in greater number than before, and in most instances with greater amplitude also. Intervals of quiet were short. The resumption and continuation of this seismic activity led to expectation of the outbreak of flow. Flow broke out, considerably lower down the slope than the place of first outbreak, in the late evening of May 21. With little doubt it was first seen by the writer, at about 11:15 P.M. It was at once brought to the attention of others at the Volcano House near by, and from here the news was spread by telephone on the eastern side of the island. On the western side of the island the outbreak was first noticed a little before midnight by Mrs. McWayne, and there the news was similarly spread.

Probably the outbreak was noticed by the writer almost as soon as it occurred. The night was clear, except for a low bank of clouds at the northeast. At 10:00 P.M. and earlier there was no suggestion of illumination anywhere along the southern segment of the mountain profile. At about 11:15 P.M. the writer went from the Volcano House to the observatory to see that the seismographs were in good working order before retiring (for, owing to the frequency and energy of the shocks, there was likelihood of the disarrangement of the struts and levers). The moon had just risen, but it was still hidden behind the bank of clouds at the northeast. However, a faint, diffuse moonlight spread over the sky. Upon mounting the observatory porch a very faint light was seen radiating from a point behind the mountain profile much lower down the southern slope than the place of first outbreak. The effect was similar to that sometimes produced here just as a planet or a bright star drops below the mountain profile. After inspection of the seismographs, however—perhaps three minutes later—this radiating light had become more definite, although the illumination of the sky by the moon had grown brighter. Almost at once it took on a pinkish hue. Then the word was spread instantly. Judging by the rapidity of its development in the first ten minutes after it was discovered, the outbreak did not take place (or more strictly, become visible from the observatory) earlier than 11:00 P.M., and probably not earlier than 11:10 P.M. Its discovery was little later than its occurrence.

During the ten or fifteen minutes after it was first seen the light at the fountainhead grew rapidly, and a small diffuse cloud of fumes appeared. This increased quickly also, and the glow steadily grew brighter and more ruddy. Soon the fumes at the top began to drift to the northwest up the mountain slope behind the profile. At the same time the progressive extension of a faint ruddy illumination down the slope behind the profile was detected. Flow had begun. As soon as possible, at about 11:45 P.M., the director of the observatory, Professor T. A. Jaggar, Jr., and the writer set out by motor and proceeded southwestward and westward to a point near the boundary of the Kona district of Hawaii beyond the western branch of the flow of 1907—a distance of about

sixty miles—and back again, arriving at the observatory at about 6:45 A.M., May 22. West of the village of Waiohinu several stops were made, both going and returning, to observe and photograph. All along the way from the observatory to the turning-point, and back again, a gradual and steady increase was noted in the height, amount, and spread of the fumes; and, until dawn, in the brilliancy of the illumination at the fountainhead. A well-defined northwest drift of the fumes in the upper strata of the air gradually developed.

From the upland flats along the road near Kahuku, and points to the westward, a long line of faint reddish illumination was seen extending to the right from the fountainhead. The course of this was judged to be about south-southeast from the source. At first it was considered to be light from the surface of a pool, but as it elongated rapidly it was soon thought to be a line of illumination above a flowing stream. This opinion was confirmed by a visit to this flow made later in the day by Messrs. J. W. Waldron and T. Hardy.

At about 4:00 A.M., May 22, we met Mr. Samuel Kauhane at the roadside gate of the ranch house at Kahuku—a man to whom the south slope of Loa was well known—and he expressed the opinion that the outbreak was higher up the mountain than the group of old cones at Puu o Keokeo. This proved to be the case.

Upon our return to the observatory a photograph (Plate III, *b*) was made at 8:30 A.M. (as early as weather conditions would permit), to show the position and development of the fume column and crown rising above the fountainhead. This view should be compared with Plate II, *a* to gain an understanding of how much lower down the mountain than the place of earlier outbreak the place of later outbreak is situated. The true azimuth from the observatory of the apparent center of this fume column at the source was found to be about S. 66° W. (the azimuths of the upper and lower limits of the greater column of the earlier outbursts were approximately S. 82° 30′ W. and S. 85° 30′ W.). This azimuth, projected upon the government map, indicated a source low on the southwest flank of the mountain, and, assuming this source to lie in the line of the south-southwest rifting from summit to sea, it was near the line of the upper branch of the flow of 1907 at an

altitude of 6,500 feet—as shown approximately on the government map—a little above Puu o Keokeo. This location was confirmed by field survey, though multiple mouths were found along a linear rift at the source, and the altitude was found to be a little higher than 6,500 feet at the lowest point of the actual source. The region of the fountainhead thus is between 30 and 35 miles west-southwest from the observatory.

In contrast to this, the region of the earlier outburst, determined by projecting the azimuths given above, is intercepted along the course of the great rift-line between approximate contour lines drawn on the government map, as follows: the upper and lower limits of the great trunk column of uprushing fumes are thus indicated at about 11,600 and 11,000 feet above sea, and the diameter of the column is thus indicated at considerably over a mile; similarly, the *approximate* upper and lower limits of the span marked by subordinate sporadic columns of rising fumes may be taken as 12,000+ and 10,000− feet, determining the width of this at five miles, or more. All these are approximate values. Nevertheless, this source is thus found to stand higher up the mountain than the early estimates placed it.

In the late afternoon of the first day of eruption, May 22, the writer returned to the southern part of the island, and spent the evening and night in observing the changes in the magnificent illumination from places along the road over the upland flats west of Kahuku. This locality was reached just at nightfall; it was then cloudy, with brief showers; however, before long the clouds lifted, though they continued to cover the sky. Little by little the character and extent of the illumination became visible.

Since the dark hours of the morning a great change had taken place. At the fountainhead both the action and the illumination were somewhat greater than when last seen in the early morning, but here the change was least. The faint red illumination extending toward the right (toward Waiohinu over upland Kahuku) had died out. But toward the left, toward Kona, a long line of brilliantly illuminated fume and cloud demarked the course of a flow which had rushed down the mountain toward Honomalino. In early evening this was still advancing at a considerable rate. The

marked illumination, which we may designate as the primary glow, was most brilliant at the fountainhead, and above the front of this flow (where its outflashing was augmented by the light from the burning forest); but also above the course of the flow between its front and source the glow was much brighter than the general sky glare. This formed a band of primary illumination whose length, as seen from the gate about a mile west of the ranch house at Kahuku, was very close to seven miles; and its brilliantly lighted arch rose about three-quarters of a mile above the mountain profile (Plate III, *c*).

A diffuse red glow covered the sky everywhere and, in early evening, low-lying cloud and fog banks clinging to the mountain slopes below the road, and illumined dimly by reflections from the cloud layer above, led to a current erroneous opinion that the flow already had advanced down the slope beyond the road in Kona.

Owing to the wretched state of the road surface, a serious congestion of motor traffic (some 250 motors headed westward and about 80 headed southward, toward a meeting-point near Honomalino, on a road too narrow for passing or turning except at widely separated places), and much uncertainty as to the exact course, rate, and behavior of the flow, the writer spent most of the night at a gate on the road about a mile west of Kahuku, where he returned after going to within three to four miles of a group of houses at Honomalino which stood in the apparent path of the flow.

The photograph (Plate III, *c*[1]) shows the scene from this station as it appeared just before midnight, May 22. In this view, of course, the bright reddish glow which covered all the sky does not appear, but simply the brilliant arch of the primary illumination, as designated above. During the night the following changes were observed:

A little after midnight there was noticed a rapid spread of very brilliant glow to the right of the fume column rising at the fountainhead. This was a conspicuous feature of the action until after 1:00 A.M. It was thought to indicate a flow toward Kahuku. This

[1] Made on a Wratten Panchromatic M plate exposed 30 minutes at *f*/6.3.

judgment was confirmed by Messrs. Waldron and Hardy, who witnessed its outrush from the high camp they occupied that night.

Beginning gradually, probably before midnight, certainly as early as 1:00 A.M., there was noted a rapid decrease[1] in the brillancy of illumination above the line of flow extending toward Honomalino. By 3:00 A.M. this, as seen from our station, was quenched completely; there remained only the diffuse glow of the clouded sky and the brilliantly lighted column of fumes rising at the fountainhead, and a much subdued glow above the front of the flow. And this last was decreasing rapidly. By 4:00 A.M. the earliest light of dawn found the illumination at the fountainhead much like that of the previous morning, with the lines of illumination above the courses of flow almost wholly quenched.

Shocks of earthquake continued to occur. Some were strong enough to disarrange the struts and levers of the seismographs. This made it inadvisable for the writer to be absent from the observatory except at times when the director could be present; so, after a brief visit to the front of the Honomalino branch, the writer returned to Kilauea.

During the evening and night of May 23–24 it was seen from the observatory that the glow had extended far to the left of the fountainhead in a direction estimated at south-southeast. No such extension of the band of illumination had been seen in the evening or night of May 22–23. This was due to the renewal of flow toward Kahuku on a much larger scale than in the beginning. Ultimately the Kahuku branches developed much greater magnitude than those in Kona. During this evening and night, May 23–24, this glow was seen through shifting clouds, so that no good opportunity for making a photographic record presented itself in the earlier hours. And, owing to his complete loss of sleep on the two previous nights, the writer undertook no prolonged watch. During the evening and night of May 24–25 this illumination appeared elongated farther to the south, and perhaps slightly abated in intensity. A photographic record of this (Plate III, *d*)

[1] It should be noted that moonrise occurred between midnight and one o'clock, but that this decrease in illumination was positive, nevertheless, as evidenced by the glow above the Kahuku tongue.

was obtained in the early morning hours of May 25, from 1:15 to 1:45 A.M. In a lessening degree this glow was seen in the evenings of May 25 and 26, and very faintly on the evenings of May 27 and 28. On the latter date it was near to the vanishing point.

II

The writer reached the front of the Honomalino branch of this flow at about 11:00 A.M., May 23, at a point about three miles, by trail, above the road. Here the flow was of *a–a*, still advancing at a slow rate of speed. This was difficult to estimate on account of the irregular character of the ground and the brief time available for watching. Though moving much more slowly than earlier, the advance was still steady. Possibly the maximum forward movement of any considerable section of the front was ten feet in an hour. The average over the whole front was less, perhaps four to five feet in an hour. At this front the flow was narrow, not more than a quarter of a mile in width. The depth at the front was variable, from six to ten or fifteen feet. Its surface, both on the top and at the front and sides, was bristling with ragged points and edges of brownish-black *a–a*. In this surface were innumerable cracks, mouths, and ovens through which the red-hot matter shone out. From many of these blue flames were flaring fitfully.

According to the writer's observation, carefully concentrated on this point, its mode of flow at this stage was as follows:

At the front, between the top and bottom, there was a slow, forward, bulging motion of the intermediate layer, from four to ten feet thick. As this progressed it produced fragmentation of the thick, stiffened surface over it, pulling and breaking this away from its contiguous parts at the more slowly moving top and bottom, and also breaking it up into an irregular mosaic with the changing curvature of the surface of the front. At short intervals blocks of the fragmented surface would be rotated into unbalanced positions, when they would spall off from their own weight and drop to the foot of the front, leaving for a moment bright, red-hot scars where they had scaled away from the matrix within. Repeated examination of these scars showed continuous red-hot matter of very viscous consistency, which cooled very quickly, tending only to

bulge out a little without spurting or jetting. No cracks could be made out on these freshly bared, red-hot surfaces. They exhibited every appearance of a viscous continuum. Once they had crusted over, however, the tendency to crack and bristle again became noticeable. At this place the fragmentation and texture-forming of these rough-surfaced blocks suggested very strongly the breaking and cracking of candy pulled too long. There was no observable gas action.

The whole effect here was one of creep, or overrunning, with the plane of maximum rate of flow intermediate between the top and the bottom. The action was that of a very viscous, fluid or plastic, substance, flowing very slowly and exerting subsurface traction upon a surface crust too stiff to *draw* or *pull* much.

It is thought that the matter was here cooled to a point where it could still flow, or creep along, under blanketing, but once in touch with the air it set so stiffly that any further strain fragmented it. Pieces artificially broken away from the bulging surfaces cooled without further fragmentation, and without the development of *a–a-texture*[1] on those surfaces of the fragments which were glowing when broken away. These exhibited the rough fracture of cold basalt. The rough, pointed, and edged texture of the natural *a–a* surface was *seen* in some cases to be due to the drawing out of points and the shaping of rough edges as the blocks were tilted and rotated away from each other, and from the plastic matrix within, while the forward bulging movement was taking place.

The mechanism of the formation of *a–a* has been considered a very involved and complicated process, and the problems suggested by it difficult of solution. The writer does not consider that the observed action described above will serve to explain all cases and details. But it does, he considers, indicate strongly that *a–a*

[1] A word concerning *a–a-texture* may not be out of place. As seen in Hawaii *a–a* is not only block-lava, heaped flows of piled blocks and fragments of various shapes and sizes, but each of these fragments is a separate unit, and its whole exterior surface, in most instances, is characterized by an exceedingly rough aggregation of points, edges, blades, spikes, knobs, etc., produced there in the process of the spalling and transport of the blocks by the *drawing*, and possibly sometimes by spurting, of the red-hot viscous basalt.

generally results from fragmentation or granulation in the course of flows of lava grown too stiff for further plastic flow under the prevailing conditions—whether this results from rapid cooling due to rapid escape of gas, to slow cooling, or to stiffening due to the development of crystalline phases, throughout the mass, or in lumps so as to form a sludge. The time is not ripe for discussion and comparison of all these factors and their interrelationships.

But the action described above, with suitably conceived modifications applicable in the region of more rapid streaming, and where greater masses and higher temperatures are involved, appears to the writer to be capable of explaining *most* of the vagaries of surface texture and miniature surface forms exhibited by *a–a* in Hawaii. Everything that the writer has seen in connection with this outbreak, and all the reports that have come to his attention, indicate that there was no *excessive* evolution of volcanic gases from the molten lava on this occasion; and all indications are that the temperature of the melt has not been excessively high. This points to a *relatively* cool and viscous fluid. And so far this supports the view of its action sketched here. It is, of course, not unlikely that still other mechanisms are involved in the forming of *a–a*, and emphatically there is no disposition to question any which rest upon observation or sound rationale. However, to the writer it seems unnecessary to appeal to unobserved, recondite, special mechanisms to explain the fragmentation and textural qualities of *a–a*. This view is in accord with the tenor of a view expressed to the writer by Dr. William T. Brigham, of the Bishop Museum in Honolulu, that *a–a* is the slush ice, or floe ice, in a cooled and freezing stream (the granulation by motion of a stiff, overcooled fluid on the point of solidifying). This seems the best short expression of the idea.

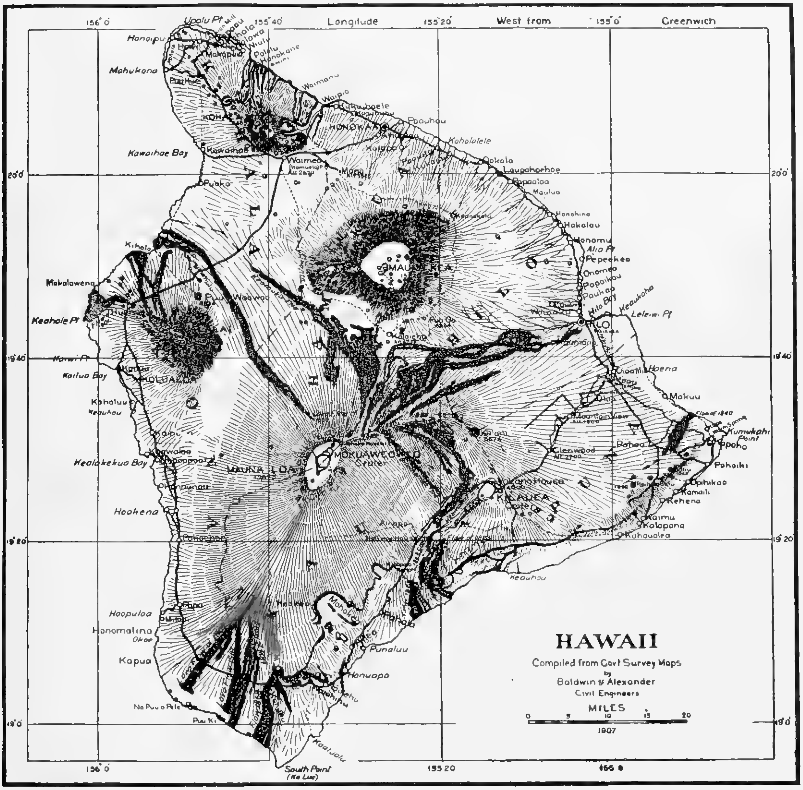
The writer saw the action just as the stream had slowed up, almost undoubtedly on account of failing supply at the source of this branch. Thus the failure of pressure from above and the radiation of heat all along the course led to rapid increase of sluggishness. At this stage of the flowing there was practically no gas action at the front. Blue fumes were rising from the surface, along with heat-disturbed air, but these were so thin that from a

tree near the front the writer was able to look a long way up the flow. The only hindrance to good seeing was the shimmer of the air produced by the heat radiation. The surface showed many oven-like openings, and a few small conelike forms were seen, but these were of temporary nature, and not true cones. No explanation of their formation occurred to the writer. One that was watched was slowly destroyed as the forward motion progressed.

The falling blocks made a tinkling sound, and the forward motion of the upper surface was accompanied by a low grinding sound, but these noises were low and inaudible at a short distance. The quiet character of the advance at this stage was very striking. At intervals loud detonations were heard. These were ascribed to the action of the hot lava on buried vegetation. The sounds made by the crackling of the falling trees and bushes were the loudest of the frequent noises, and the crackling produced by the burning of green vegetation was the most continuous and conspicuous. At this stage of the flow its approach was so quiet that it gave practically no warning at a distance of fifty yards. Trees were being felled by the flow, partly by burning through at the stump, but in some instances by overturning as a result of the forward motion of the flow.

There were smells of subliming sulphur, sulphur acids, and of cinders and charcoal. None of these was strong enough to be very annoying. Others reported the smell of coal gas. This was not noted by the writer, but was noticed by a large number of people, and the fact must therefore be accepted. This was in the wooded region, and here these carbon-gas odors could be ascribed to the action of the lava on vegetation. However, along the Kahuku branch of the flow such carbon-gas odors were plainly noticed by many at points well above the wooded region, where vegetation was so scanty as to be negligible. And some have reported noticing these odors near the lower end of the source in a barren region where there is strictly no vegetation. It seems, therefore, that carbon gases almost unquestionably were emitted from the lava of this eruption.

[*To be continued*]



Map of Hawaii, showing *diagrammatically* in red the flow of 1916, and the upper outbreak source, with older flows in black. On this map the upper portion of the flow of 1907 is not indicated *precisely*. This passed down the mountain on the west side of Puu o Keokeo.

a *b*

c *d*

Views *a*, *b*, *c*, and *d* show successive stages in the development of the fume cloud [*a* at 7:45, *b* at 8:00, *c* at 8:30, and *d* at 9:05 A.M.] of the earlier outbreak on May 19, 1916, as seen at a distance of about 25 miles, in a direction a little south of west, from the Hawaiian Volcano Observatory.

a *b*

c *d*

a, showing a later stage, at 10:00 A.M., in the spread of the fume cloud of May 19, 1916.

b, showing the fume cloud above the head of flow at 8:30 A.M., May 22, 1916, as seen at a distance of 30–35 miles, in a direction S. 66° W. from the Hawaiian Volcano Observatory.

c, showing the brightly illuminated arch, or "primary glow," above the source, and the course of the Honomalino stream, as seen just before midnight, May 22, 1916, at a distance of about 10 miles in a direction about N.N.W. from near Kahuku. This illuminated band or arch was about 7 miles in length and about $\frac{3}{4}$ mile in height. Besides it, a bright, diffused red glow covered the entire clouded sky—an effect not shown by the view.

d, a view from the Hawaiian Volcano Observatory exposed from 1:15 to 1:45 A.M., May 25, showing the illuminated fume cloud above Kilauea (lower left) at a distance of $2\frac{1}{3}$ miles from the camera, of about 1,500 feet spread, and the illumination above the Kahuku stream (upper right), partly hidden by clouds at the south, distant 30–35 miles, with a spread of about 5 miles and a height of a little less than $1\frac{1}{2}$ miles at maximum.

AGE AND STRATIGRAPHIC RELATIONS OF THE OLENTANGY SHALE OF CENTRAL OHIO, WITH REMARKS ON THE PROUT LIMESTONE AND SO-CALLED OLENTANGY SHALES OF NORTHERN OHIO

AMADEUS W. GRABAU
Columbia University

The name "Olentangy shale" was given by N. H. Winchell[1] in 1874 to the light-gray soapy shales which underlie the Ohio shale and are exposed on the Olentangy River and its tributaries in central Ohio. Winchell regarded this shale as belonging with the Huron shale which overlies it, but since his day this deposit has usually been classed with the Middle Devonian,[2] and has been made in a general way the equivalent of the Hamilton formation of New York. The reason for such a grouping seems to have been the fact that in northern Ohio a shale and limestone series lies between the Huron shale and the Delaware limestone and so holds essentially the position occupied by the Olentangy shale in central Ohio. I have elsewhere[3] proposed to call this series in northern Ohio the Prout series, from its exposures near the station of that name. In the summer of 1914 I made a detailed study of the several outcrops of this formation in the region about Sandusky, collecting at Plum Creek and paying special attention to the contact of the Prout and Huron formations shown in the exposures at Slate Cut on the Lake Shore Railroad, halfway between Sandusky and Huron, and in the "Deep Cut," about a mile northeast of Prout Station. A summary of my observations was included in the *Report on the Devonic Formations of Michigan* submitted toward the end of that

[1] *Geol. Surv. Ohio*, II, Pt. 1, pp. 287–89.

[2] The author prefers the term "Devonic" to "Devonian," but has changed it in conformity with the usage of the *Journal*.

[3] "Olentangy Shale of Central Ohio and Its Stratigraphic Significance" (Abstract), *Bull. G.S.A.*, XXVI (1915), 112.

year, but unfortunately not yet published. I quote from the manuscript:

The upper $4\frac{1}{2}$ to 5 inches of the Prout has a peculiar character in that it is full of pyrites, is irregularly bedded, and contains much glauconite. Black shale specks and fish teeth are found in the upper half-inch. This upper part of the limestone suggests a weathered and reworked portion very different from the lower part, which is also dolomitized. Some doubtful limestone pebbles have been found at the contact line in the base of the Huron shale, but they are not sufficient in number to be of much value. Altogether, the evidence is inconclusive, but it is not against the assumption of a disconformity [between the Prout and the Huron]. . . . .

The abrupt contact and the absence of intergrading are further indications of a pronounced change in sedimentation with a long time interval between the two formations. A comparison of the fauna of the Prout with that of the Traverse group of Michigan, gone into at some length in my report, shows the former to correspond to the lower Traverse of Michigan, i.e., to the beds below the Alpena limestone. I quote again from my manuscript report:

This means that the upper beds were never deposited or that they were removed by erosion prior to the deposition of the black shale, for no one would consider the black shale in any way contemporaneous with the upper Traverse beds of Michigan. Thus an unquestioned time interval is indicated, and since we find elsewhere the black shale disconformable upon the Traverse or other Mid-Devonic beds, we need not hesitate to assume the same relation for northern Ohio. . . . . Compared with the sections in northwestern Ohio and in Canada, the evidence becomes quite conclusive that between the Prout and the Huron there is an unrecorded time interval.

Quite recently Dr. Stauffer[1] has returned to a discussion of the correlation of the Prout formation on the basis of its fossils, which he listed in an earlier publication.[2] He comes to the conclusion that the Prout limestone represents the Encrinal limestone of Eighteen Mile Creek,[3] and the shales below it, the lower Hamilton shales of western New York.[4]

[1] C. R. Stauffer, "The Relationships of the Olentangy Shale and Associated Devonian Deposits of Northern Ohio," *Jour. Geol.*, XXIV, No. 5 (July-August, 1916), pp. 476–87.

[2] *Geol. Surv. Ohio. Bull. No. 10*, 4th Series, 1909.

[3] I have proposed the name Morse Creek limestone for this Encrinal of western New York at the meeting of the Geological Society of America, December, 1914, and in the report on *The Devonic Formations of Michigan* above referred to. It is an older limestone than the Encrinal or Tichenor of central New York. See *Bull. G. S. A.*, XXVI (1915), 113.

[4] Now designated the Wanakah shales by me.

That exact correlation with the Encrinal limestone of Lake Erie is possible may perhaps be doubted, since the calcareous beds increase in number westward. The Encrinal (Morse Creek) limestone is the attenuated eastward extension of the great Alpena limestone of Michigan, and the Prout limestone probably represents one of the lower Traverse limestones of Michigan. Still, Stauffer is undoubtedly correct when he makes the age of the Prout limestone and associated shales lower Hamilton, and it is gratifying to me to feel myself in substantial agreement with one who has made such prolonged studies of these formations and faunas.

When it comes to the Olentangy shale of central Ohio, however, Stauffer and I are in cordial disagreement. He makes it the equivalent of the Prout limestone and shales of the north and so of Hamilton age, while I regard it as a part of the Huron shale series, and referable to the Upper Devonian.

Although I had held this view for many years, it was not until the summer of 1914 that I was enabled thoroughly to test my conclusions in the field. At that time I examined all the important exposures of the formation in Delaware County, beginning with Winchell's type locality, on the Olentangy River. A new section opened here for commercial purposes made a careful study possible. The actual contact between the Olentangy and Huron is sharp, but perfectly even and uniform. In the upper portion of the gray Olentangy are several thin bands of black or chocolate-colored shale of the type of the Huron.

The bedding of the Olentangy shale is chiefly brought out by the occurrence of thin bands of dark shale, and by more or less continuous layers of flat concretions. These are calcareous, up to 2 feet long by 1 foot thick, but mostly smaller. They abound in iron pyrites, as does also the Huron shale overlying. In some sections, as in the Deep Run and Lewis Center and Bartholomew runs, the lower part of the Olentangy shale contains thin bands of impure limestone. In one of these I found fish scales. In all the sections, however, are found the thin bands of black shale in the upper part of the gray, thus indicating a transition of the one formation into the other. At the contact with the first great mass of Huron shale there are sometimes found indications of a slight drying of the surface of the Olentangy, with the formation of cakes

or scales of dry, gray mud, which were then incorporated in the black mud. This is just what we should expect if the deposition of the gray muds had come to an end and sedimentation were renewed by the influx of the black mud from another source. Essentially, however, deposition here was continuous, and after the commencement of the sedimentation of the black Huron mud, there was a temporary recurrence of the gray sedimentation, so that we see today a 10-foot bed with all the characters of the typical Olentangy lying above a considerable thickness of black Huron shale. In both the upper and the lower part of this interbedded mass of Olentangy occur thin bands of black shale, as they do in the typical Olentangy lower down.

The basal contact of the Olentangy and Delaware is not shown in any section which I visited, but the Olentangy could be examined to within a few feet of the contact. There is no interbedding of the Delaware and the Olentangy; the change in material is absolute. The concretionary limestones of the Olentangy are very different in character from the calcarenytes of the Delaware limestone. The concretions appear to be of the subsequent type found in the gray Cashaqua shales of western New York, to which the Olentangy shales bear the closest resemblance. Like them, they are unfossiliferous, though fossils are found in some parts of the Cashaqua. The barren nature of both of these shales is in striking contrast with the highly fossiliferous character of the Hamilton shales of western New York, Canada, Michigan and even northern Ohio. A few fragmentary fossils have been found in the calcareous beds, but these might easily be residual specimens weathered from the underlying limestones and incorporated in the new sediment. Such undoubtedly is the origin of the lenticular bed of crinoid fragments found in the type section, which does not exceed 5 inches in thickness. This is apparently a reworked mass of crinoidal fragments dissociated by the weathering of an older crinoidal limestone.

The relationships here presented admit of only one conclusion, namely, that the Olentangy shale is a part of the Upper Devonian, representing a special type of sedimentation, such as characterized the early Upper Devonian sediments of western New York. Sedi-

mentation was continuous from Olentangy into Huron time, but the Huron type alone is represented in northern Ohio, where by overlap it rests upon the eroded surface of the Prout limestone. The latter is absent in central Ohio, where either it was never deposited, or, what is more likely, it was removed by pre-Huron erosion. This erosion extended down to the Delaware limestone, though it is not impossible that a part of the lower Prout series is represented in the central area by the Delaware limestone itself. If the name "Prout" is to be restricted to the limestone member of the northern series, then the shale below it must receive another name. It certainly is not Olentangy, which name belongs to the earliest Upper Devonian formation of central Ohio. In my report on *The Devonic Formations of Michigan* I have proposed the name "Arkona beds" for the shales lying below the Encrinal limestone of the Thedford, Ontario, region. If, as Stauffer holds, the shales below the Prout limestone are the equivalent of these Ontario shales, which he calls Olentangy, then the name "Arkona" may also apply to them. It may be wiser, however, to refer to them as the Plum Creek shales, since the distance between Arkona and Plum Creek is too great to permit of positive identification. True, Dr. Shimer and myself correlated the Encrinal limestone of Thedford with that of western New York, on the basis of faunal characters, and this correlation may be correct. At the same time, we now know that the Encrinal of western New York (Morse Creek) and that of central New York (Tichenor) are not the same beds. I have also shown[1] that the faunas of the shales below the Morse Creek in Eighteen Mile Creek occur in the shales above this limestone 60 miles to the east, where they are not found below that limestone. I have also shown that this typical Hamilton fauna is absent from the beds above the Morse Creek limestone at Eighteen Mile Creek, there being thus a complete inversion of faunas. On purely faunal grounds the shales below the Morse Creek at Eighteen Mile Creek would be correlated with the shales above that bed at Moscow and elsewhere in the Genesee Valley. The explanation of this and the relation of the western New York Hamilton faunas to the Thedford and Michigan Traverse

[1] "The Faunas of the Hamilton Group of Eighteen Mile Creek and Vicinity in Western New York," *16th Annual Report, N.Y. State Museum*, 1898, p. 330.

faunas is fully set forth in the unpublished report referred to. There, too, it is shown that the faunas of the Traverse group on opposite sides of the state of Michigan differ materially, while identification of equivalent limestones and shales between the two sections is impossible. All of these facts would lend some force to the suggestion that precise correlation of the Prout limestone and Plum Creek shales with the Encrinal limestone and Arkona shales of the Thedford region should not be too rigidly insisted upon. Nevertheless, we may with Stauffer lay much stress on the presence of the *Bactrites* layer at about 25 feet below the Encrinal at Arkona and a similar distance below the Prout limestone at Plum Creek,

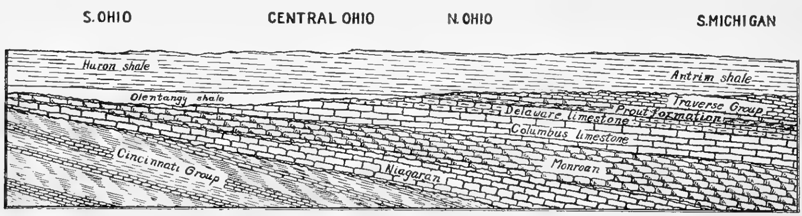


FIG. 1.—A generalized north-south section through Ohio and southern Michigan, showing the relations of the Olentangy shale and the Prout formation.

containing at both places pyritized *Bactrites arkonensis* and *Tornoceras uniangulare*, besides *Nucula triqueter* and *Leda rostellaria*. Then, too, as Stauffer has shown, the faunas of the Prout limestones of this and of the Encrinal of Ontario are very similar, the latter containing over 75 per cent of the species found in the former. On the whole, therefore, Stauffer's position seems well taken, and we may accept his correlation of the Prout limestone with the "Encrinal" of Thedford and perhaps with the Encrinal (Morse Creek) of western New York.

We cannot, however, use the name Olentangy for the shales below these horizons, and therefore the Canadian term "Arkona shales" is preferable. This name may be then applied likewise to the shales of Plum Creek. The comparative study of the brachiopods of these various shales, now in process, will throw further light on the provincial relationships of these formations.

Let us return once more to the typical Olentangy shale of central Ohio, which we have seen is of Upper Devonian age. It rests disconformably upon the Delaware limestone, which represents some of the lower Traverse beds of the Michigan region. There is thus a great hiatus between the Delaware limestone and the Olentangy shale in central Ohio, cutting out the greater part of the Traverse group. This hiatus increases southward, so that in Pickaway County the Olentangy shale lies in places upon the lower Columbus and elsewhere upon the Monroan, and in all cases it is succeeded by the black Huron shale. At Bainbridge, in Ross County, it even rests upon the Niagaran. The Olentangy is still represented at Vanceburg, Kentucky, on the Ohio River and near Fox Springs, Fleming County, Kentucky, according to W. C. Morse. A generalized north-south section through the region named brings out the magnitude of the post-Traverse erosion, and also shows that the Olentangy shale is of the nature of a lentil, disappearing to the north and to the south. The source of the Olentangy was probably local and circumscribed, representing perhaps an accumulation in Upper Devonian time of a residual soil produced from the weathering of the underlying rocks. It may possibly be an extension of some of the eastern gray shales of the Upper Devonian, such as the Cashaqua. The Black Huron shale I hold to be a deposit of carbonaceous mud washed into the shallow Upper Devonian sea by the rivers coming from the Devonian peneplanes to the south and representing probably our best case of an estuarine deposit in the American Paleozoic. The details of this and the relation of the Huron to the Chattanooga shale, which latter I consider mostly a terrestrial residual soil, reworked in Mississippian time by the encroaching sea, are set forth at length in the monograph on *The Devonic Formations of Michigan* to which reference has several times been made.

THE HISTORY OF DEVILS LAKE, WISCONSIN

ARTHUR C. TROWBRIDGE
University of Iowa

The vicinity of Devils Lake, Wisconsin, has long been used as a field of instruction in geology in the Middle West. The pre-Cambrian igneous, sedimentary, and metamorphic rocks, the Paleozoic history, the economic products, the general results of glaciation, the origin and history of the lake, have all been reported in a general way.[1] It has been the privilege of the writer to conduct several courses in the district, to work over the data collected and reported by previous investigators, and to work out additional points not completed by them. He finds that the general history of the district may be incorporated in an account of the history of the lake and its basin.

The purpose of this paper is to bring together all the events in the history of the lake basin, and to include some heretofore unpublished conclusions as to the history of the lake, its past and present sources of supply, and outlets once established but now abandoned. This involves repetition of some facts already published, and leads beyond the present boundaries of the lake basin.

LOCATION AND DESCRIPTION

Devils Lake is an almost rectangular body of fresh water $1\frac{3}{10}$ miles long in a north-south direction and $\frac{1}{2}$ mile broad, situated in Sauk County, Wisconsin, 3 miles south of Baraboo, 40 miles north by northwest of Madison, 80 miles southeast of LaCrosse, and 100 miles west by northwest of Milwaukee.

The district in which the lake lies is one of extraordinary high relief for the central Mississippi Basin (about 800 feet) and of considerable irregularity. The topography is dominated by two

[1] R. D. Salisbury and W. W. Atwood, *Bull. No. 5, Wis. Geol. and Nat. Hist. Surv.*, pp. 51–55; Samuel Weidman, *Bull. No. 13, ibid.*, pp. 109–14; Lawrence Martin, *Bull. No. 36, ibid.*, pp. 177–78.

ridges or "ranges," known respectively as the North Range and the South Range. These are the outcropping edges of the hard Baraboo quartzite formation which forms here an asymmetric syncline, the north limb of which is nearly vertical and forms the North Range and the south limb of which has an average dip of 18° and forms the broader and higher South Range. The ranges are 24 miles long in a general east-west direction, and they converge at either end. The South Range is distinctly flat at and near the top, the plain summit areas lying between 1,400 and 1,480 feet A.T. There are also smaller areas of flattish land at 1,200 feet, 400 feet below Sauk Point, which is the highest point in the district, and 400 feet above main drainage lines. The summit of the North Range is also flattish, its evelation being about 1,200 feet.

The district is drained by the Wisconsin and Baraboo rivers and their tributaries. The Wisconsin River flows from the Dells, 17 miles north of Baraboo, in a broad curve past the east end of the ranges at Portage to Prairie du Sac, where it may be said to leave the district. Baraboo River enters the district at Ableman through the North Range, in a gap known as the Upper Narrows, flows in a general easterly direction between the ranges past Baraboo, cuts back through the North Range at the Lower or Baraboo Narrows, and joins the Wisconsin River near Portage.

Devils Lake occupies the northern portion of the only gap there is through the South Range. This gap has the form of a broad open curve with a north-south course in its northern portion, an east-west course in the middle of the range, and a northwest-southeast course at the south edge of the range. About one-fourth of the length of the gap is occupied by the lake. The surface of the lake is at 960 feet A.T. which is 160 feet above the Baraboo River to the north, 200 feet above the Wisconsin River to the south, and about 500 feet lower than the flat top of the range east, west, and southeast of it (Plate I).

STRATIGRAPHY

The rocks of the district about Devils Lake include the Huronian, Cambrian, and Ordovician, each system being represented by more than one formation.

The oldest rocks of the district are granite, diorite, and rhyolite, which lie around the borders of the quartzite syncline and seem to form the basement upon which the quartzite was deposited. Next above the igneous rocks lies the Baraboo quartzite, which in turn is overlain conformably by the Seeley slate and the Freedom formation. The Baraboo, Seeley, and Freedom formations are all involved in the folded structure of the district, although the Seeley and Freedom beds do not outcrop. The total thickness of the Proterozoic formations is about 6,000 feet, the quartzite alone measuring in the North and South ranges about 5,000 feet.

There is a great unconformity between the Proterozoic and Paleozoic groups of rock. After the Proterozoic formations were deposited and folded, the region was eroded in one or more cycles until the surface in this district had a relief of at least 1,300 feet, and upon this rugged surface the Cambrian rocks were deposited.

The Cambrian system includes the Potsdam sandstone, between 600 and 700 feet thick where thickest, the Mendota limestone, 3–11 feet thick in the Devils Lake district, and the Madison sandstone, 80–90 feet thick. This is a conformable series and the strata are essentially horizontal. Away from the ranges the top of the Madison sandstone is about 1,020 A.T., but the standsone laps up on the ranges to altitudes of 1,200 feet or higher.

Only the Prairie du Chien and St. Peter formations of the Ordovician system now appear in the vicinity of Devils Lake, although it is nearly certain that younger formations were deposited here originally and have been eroded away.

The Prairie du Chien formation overlies the Madison sandstone conformably, but outcrops in only a few localities within the boundaries of the Devils Lake district. It is hard, cherty dolomite. Its average thickness in the Mississippi Valley is about 200 feet, although in the immediate vicinity of Devils Lake its greatest thickness is 20 feet.

An unconformity is known to exist between the St. Peter and Prairie du Chien formations in Iowa, Illinois, Wisconsin, and Minnesota, and is well represented in the Devils Lake district. If the total thickness of 200 feet of Prairie du Chien dolomite was

deposited here, all but 20 feet was eroded away a mile southeast of the Baraboo Narrows, before the deposition of the St. Peter sandstone. At Gibraltar Rock, 8 miles southeast of Devils Lake, there is a thickness of 73 feet of Prairie du Chien dolomite between the St. Peter and Madison sandstones on the southeast slope of the hill and none at all on the southwest slope, the St. Peter sandstone lying directly on the Madison sandstone on the southwest side. It is believed that the Prairie du Chien dolomite was entirely removed in other places also, before the St. Peter sandstone was deposited, as on the hill a mile south of the Pewits Nest (see Plate II). The St. Peter formation is a massive, medium-grained, quartz formation so similar to the Madison that the two cannot be separated on lithologic grounds. The St. Peter sandstone is thought by some geologists to be of eolian origin, but most of it at least seems to be marine. In thickness the St. Peter varies from a few feet to more than 200 feet within the district. The variation is due to the erosion surface on which it lies, and to post-St. Peter erosion of its surface.

Platteville limestone, Galena dolomite, and Maquoketa shale are all found at Blue Mounds, 26 miles to the south of Devils Lake, and its seems certain that these formations once covered the Devils Lake district. If so, they were eroded away in some late Paleozoic, Mesozoic, or Cenozoic erosion cycle, leaving no trace of their previous existence.

The previous existence of rocks of Silurian age in the district is proved by the finding of Niagaran fossils in a gravel deposit on the summit of the quartzite range east of Devils Lake.[1]

Aside from the late Ordovician and mid-Silurian rocks which once undoubtedly covered the region around Devils Lake, it is entirely possible, though not proved, that formations of Devonian and Carboniferous age were deposited also and were subsequently eroded away. Certain it is that thick deposits of rock were laid over the St. Peter sandstone.

Glacial drift and lacustrine deposits of late Pleistocene age lie unconformably on all the older rocks of the district (Plate II).

[1] R. D. Salisbury, *Jour. Geol.*, III, 655–67.

THE EARLIEST RECORD

The history of the depression in which Devils Lake lies goes back to pre-Cambrian times. Cambrian sandstone lies in the gap, (1) at the north end of the east bluff one mile south of the northernmost outcrop of quartzite in the South Range, 240 feet above lake-level and 270 feet below the summit plain; (2) near the foot of the west bluff, one-fourth mile north of the north end of the lake, 60 feet above lake-level and 450 feet below the tops of the bluffs; (3) at the southwest corner of the lake at "Messenger's End," where it extends from a few feet above lake-level to an altitude of 1,200 feet at the divide between Devils Lake and Skillett's Creek; and (4) forming a hill or bluff on the north wall of the gap $2\frac{1}{2}$ miles east of the lake. At the last-designated point the sandstone extends to 900 feet A.T., which is below lake-level. The presence of Cambrian sandstone at levels near that of the present lake surface, near the north end, near the southeast end, and near the center of the gap shows clearly that there was a depression or that there were depressions here before the advance of the Cambrian sea. The facts might be interpreted in one of two ways:

1. The simplest explanation lies in the assumption that after the pre-Cambrian formations were folded, the surface was eroded and reduced to a peneplain on which a river meandered, that this plain was uplifted relative to the sea, and that the district had reached late youth or early maturity in a second cycle of erosion before submergence by the Cambrian sea. Under this interpretation the original gap is a pre-Cambrian intrenched meander. The ancient peneplain may be represented by the present summit plain of the district, or it may have been entirely destroyed in subsequent periods of erosion.

2. The conditions, however, might be almost equally well explained by assuming that the district was in maturity either of its first or of some later cycle of erosion when the Cambrian sea advanced, that at that time a deep valley existed in the range with its head in the valley of Messenger's Creek and discharging eastward and southeastward, and that another stream headed somewhere north of Messenger's Creek and flowed northward into the Baraboo valley. This would not necessitate more than one cycle of

erosion in pre-Cambrian times nor would it preclude more than one cycle.

After the long series of events during the Paleozoic and subsequent history of the district, it does not seem possible to determine which of the foregoing interpretations is correct. However, some light is thrown upon the matter by consideration of the pre-Cambrian history of Wisconsin, and the principles of stream adjustment. It has been demonstrated by Weidman[1] and Martin[2] that the surface of Wisconsin was degraded to a peneplain in pre-Cambrian times, that this plain slopes south and is buried beneath Cambrian sediments at an altitude of about 300 feet in the latitude of Devils Lake, and that the quartzite ranges stood as erosion remnants on this plain. Well-records in the Baraboo valley show that the pre-Cambrian surface within the inclosure made by the ranges is as low at least in some places as 340 feet A.T. A stream must therefore have had entrance to the inclosure and a means of escape from it. A broad, continuous, stream-made gap, filled with Cambrian sediments, cuts through the North Range northwest of Baraboo, and is probably the line of entrance or exit of a large pre-Cambrian stream. The other gap, either entrance or exit, is not known unless it be the Devils Lake gap. Neither the Lower nor the Upper Narrows seems to be large enough and they have not yet been proved to be pre-Cambrian in age. It is improbable that there is a buried gap, undiscovered, either in the North or the South Range, which might have conducted the river in or out of the area between the ranges. It is unlikely also that two streams would adjust themselves as postulated in the second case above. A stream working headward into a hard, high ridge with a steep slope would hardly develop a course other than one more or less nearly straight and nearly normal to the trend of the ridge. But the stream flowing southeastward from Messenger's Creek must have had a course which was distinctly curved, had supplementary angles of 30° and 150° with the trend of the ridge, and was oblique to the dip of the rocks. On the other hand, the

[1] Samuel Weidman, *Bull. 16, Wis. Geol. and Nat. Hist. Surv.*, pp. 385–95, 592–600; *Jour. Geol.*, XI, 289–313.

[2] Lawrence Martin, *Bull. 36, Wis. Geol. and Nat. Hist. Surv.*, pp. 347–73.

freshness and apparent youth of Devils Lake gap, and its size, harmonious with the dimensions of the Upper and Lower Narrows, suggest that these three gaps were cut at the same time and during some post-Silurian period. And yet Devils Lake gap may have carried a large river in pre-Cambrian times and the gap may have been reoccupied at a later time when the two Baraboo narrows were cut.

Whether the pre-Cambrian Devils Lake gap was cut by a single intrenched meandering stream, or by two streams with a col between them, the depression must have been a deep one. The rim of the canyon is today represented by the 1,470-foot summit plain, and the pre-Cambrian rim may have been higher than this. Cambrian sandstone in the gap is known as low as 900 feet A.T. The depression must therefore have been at least 570 feet deep in pre-Cambrian times. Certainly if the gap was cut by the same stream which reduced the inclosure between the ranges to 340 feet A.T., and probably if it was cut by two streams tributary to main drainage, the bottom of the gap at the end of pre-Cambrian times was not much higher than 340 feet A.T. The pre-Cambrian gap was then probably not far from 1,100 feet deep. The whole district at this time is known to have had a relief of 1,200 or 1,300 feet.

PALEOZOIC HISTORY

The Paleozoic, marine, sedimentary rocks of the district record the second important step in the known history of the district.

Upper Cambrian sandstone is found on the ranges to an altitude of 1,200 feet A.T. and probably exists at slightly higher levels. On Wood's Quarry Hill, 3 miles northwest of the lake, rounded pebbles of quartzite are found in the uppermost beds of the Madison formation where it is overlain conformably by Ordovician dolomite, giving evidence that quartzite was exposed on near-by land up until the very end of the Cambrian period. In the light of these facts, it is believed that the South Range was an island in the Cambrian sea, and that the Devils Lake gap was not filled to a higher level than 1,020 feet, although the sea seems to have reached at least to 1,200 feet.

But deposition did not end with the Cambrian period. The Prairie du Chien and St. Peter formations, or their time equivalents, must have been deposited in the gap. It is clear that the sediments of the Prairie du Chien stage did not fill the gap, for the base of this formation has an elevation of 1,020 feet in the vicinity, and it would require a thickness of 500 feet to have filled the gap. As the formation is nowhere known to be so thick, it is probable that a sag existed at the site of the present gap, when the Prairie du Chien sea had withdrawn, and it is possible that the gap was again occupied by running water and partly re-excavated before the deposition of the St. Peter sandstone. As the St. Peter sandstone is not found much above 1,300 feet in the district, it seems clear that the gap was not entirely filled with this deposit.

Although no traces of the Platteville, Galena, and Maquoketa formations are found in Devils Lake gap or in its immediate vicinity, it seems clear that these formations, or their time equivalents, were deposited in the gap, filled it, and buried it, for if the dip of these formations be projected northward from their existing altitude at Blue Mounds and other points to the south, the bottom of the Maquoketa formation would lie 200 or 300 feet above the summit plain on the South Range. Gravels containing Niagaran fossils are found to the very top of the range on the flat summit plain east of the lake, showing that this formation added its thickness to the sediments which buried the filled gap and the ranges.

If still younger Paleozoic formations were deposited over the district and over the filled gap, they have left no record. So far as the records go, the Paleozoic sea retreated finally at some date after the Niagaran epoch. These seas probably left the district essentially flat, with the rough surface of the quartzite buried beneath thick Paleozoic sediments. At this time there was no Devils Lake gap as a topographic feature, but there was a previously existing gap, filled with sediments and buried by formations which also covered the ranges deeply.

POST-PALEOZOIC—PRE-GLACIAL HISTORY

The record of the history of the gap following the final withdrawal of the Paleozoic seas and antedating the advance of the

Wisconsin glacier is to be read only from the study of the topography and surficial deposits of this and surrounding districts.

The flat summit areas at various places on the South Range at altitudes between 1,400 and 1,480 feet, lying across the beveled edges of the quartzite beds, can be interpreted only as an ancient plain of degradation now almost destroyed by streams working in a later erosion cycle. The peneplain might be considered to be of pre-Cambrian age but for the fact that there are stream gravels on its surface which are composed of Paleozoic rocks, and contain fragments in which are imbedded Niagaran fossils. Associated with the gravel there are numbers of potholes which are not filled by Paleozoic sediments and which probably are of post-Niagaran age. The idea that the flat is a remnant of the old pre-Cambrian plain buried by Paleozoic formations, resurrected by later erosion, and becoming again the site of deposition as a part of the later peneplain, is perhaps tenable, although hardly probable, for the extension of this plain has now been traced west into Iowa and south into Illinois, in both of which states it cuts across the beveled edges of the Potsdam, Prairie du Chien, St. Peter, Platteville, Galena, and Niagara formations in order.

It is not to be understood that this erosion surface had reached a final stage of degradation and was perfectly flat. It is made clear by a study of the Devils Lake district, as of other districts where the plain is known, that it had considerable relief. West of Devils Lake the surface of the plain is 1,400 feet A.T., which seems to be the altitude of the portion which was brought to grade. East of the lake the gravels lie on a flattish surface at 1,470 feet, and quartzite at Sauk Point reaches an altitude of about 1,600 feet. Before this surface was dissected, it had a relief of 200 feet in the Devils Lake district, and the gravel occupies a position between the lowest and highest portions of the surface. The gravels probably were not brought from a distance by a long and large stream at grade, but were more likely to have been deposited by a stream tributary to main drainage, the tributary having enough velocity to carry gravel and to cut potholes. The gravels include no material which could not have been derived from local formations. On the other hand, the relief of the surface must have been much

less than that of the present surface, and Devils Lake gap could not have existed at the time.

The exact age of this erosion surface is still an open question. Where the plain and the gravel associated with it are known outside this district, they have been assigned by different writers to different ages. Winchell[1] long ago correlated these gravels in Minnesota tentatively with the Cretaceous, and following his lead Bain,[2] Calvin,[3] Grant and Burchard,[4] Hershey,[5] and others have considered the plain to have been formed chiefly during the Cretaceous period. This correlation is, however, somewhat doubtful, for the reason that it has never been proved that the gravel on the plain in Minnesota is of Cretaceous age. It seems to lie on the Cretaceous, a relationship which tends to show that the plain cuts across the edges of the eroded Cretaceous rocks and is therefore post-Cretaceous in age, just as the fact that it cuts across the Paleozoic sediments proves that it is younger than those sediments. Most likely the plain is of Tertiary age. The evidence of this has been presented by Salisbury[6] in an article in which he suggests the correlation of these patches of gravel with the Lafayette formation farther south.

It is at least clear that the Devils Lake gap remained filled with Paleozoic sediments while this plain was being formed, and that the time involved was long.

There are strong suggestions of a second flattish erosion surface with remnants at about 1,200 feet. Representatives of this surface may be found (1) cutting across the beveled edges of the vertical quartzite beds of the North Range at the Upper Narrows, (2) at the Lower Narrows, (3) 2 miles northeast of Denzer, (4) on the summit of Old Flat Top, 1 mile southeast of the Lower Narrows, (5) on the top of Gibraltar Rock, 1½ miles west of Okee, and (6) forming saddles or low divides in the South Range, as on the

[1] N. H. Winchell, *Geol. and Nat. Hist. Surv. Minn.*, I, 309–31, 353–56.

[2] H. F. Bain, *Bull. U.S. Geol. Surv., No. 294*, pp. 11–16.

[3] Samuel Calvin, *Iowa Geol. Surv.*, IV, 43.

[4] Grant and Burchard, Lancaster Mineral Point Folio, *U.S. Geol. Surv.*, p. 2.

[5] O. H. Hershey, *Am. Geol.*, XX, 246–59.

[6] R. D. Salisbury, *Jour. Geol.*, III, 655–67.

divides between the North Fork of Messenger's Creek and Skillett's Creek, between the South Fork of Messenger's Creek and an unnamed south-flowing stream, between Pine Creek and Otter Creek, etc. Because the remnants of this plain within the district cut across the quartzite beds and lie on St. Peter sandstone, and because most of the streams of the district find their sources on the plain, the remnants are believed to represent parts of a plain of erosion developed at this level, but now mostly dissected. This interpretation is greatly strengthened by the finding of a similar plain, bearing the same relation to the older plain, and cutting across the edges of eroded formations, at many places outside the district under consideration, as, for instance, in the Richland Center quadrangle, in the Sparta quadrangle, in the Lancaster and Mineral Point quadrangles, in the eastern portions of the Waukon and Elkader quadrangles in Wisconsin, in Jo Daviess County, Illinois, in Allamakee, Clayton, and Dubuque counties in Iowa, and at various places in southeastern Minnesota.[1]

If this plain is correctly interpreted, it records the following steps in the history of the district in general and of Devils Lake gap in particular. After the 1,400–1,480 foot plain was developed, the district was uplifted relative to the sea-level of that time to an amount of approximately 200 feet, the streams were rejuvenated, and reached grade again at levels 200 feet lower than the first plain.

It was during this cycle of erosion that Devils Lake gap was re-excavated and the Upper and Lower Narrows were formed, or re-formed if they are of pre-Cambrian age. In the formation of these post-Paleozoic gaps problems of stream adjustment are involved. Martin[2] expresses disbelief in the two peneplains in this part of the country, considers that all post-Niagaran and pre-Wisconsin erosion took place in a single cycle, and believes that the Devils Lake gap, and the two Baraboo gaps in the North Range,

[1] O. H. Hershey, *Am. Geol.*, XX, 246–59; U. B. Hughes, *Proc. Iowa Acad. Sci.*, XXIII, 125–32; W. D. Shipton, Master's thesis, University of Iowa Library; U. S. Grant and E. F. Burchard, Lancaster Mineral Point Folio, *U.S. Geol. Surv.*, p. 2; A. C. Trowbridge and E. W. Shaw, *Bull. No. 26, Ill. Geol. Surv.*, pp. 136–44; A. C. Trowbridge, *Bull. Geol. Soc. Am.*, XXVI, 76.

[2] Lawrence Martin, *Bull. No. 36, Wis. Geol. and Nat. Hist. Surv.*, pp. 63–70 and 177.

were made by the Wisconsin and Baraboo rivers developing their courses on the surface of the Paleozoic rocks, cutting down through these rocks and becoming superimposed on the ranges, and holding their courses. In the case of Devils Lake gap, at least, this hypothesis seems to involve too nice a coincidence. Whether the pre-Cambrian gap was continuous or made up of two valleys with a col between, Martin's idea would mean that a crooked stream starting on a surface 1,200 feet or more above final grade, cuts down more than 300 feet, then develops a flat surface and deposits fine gravel without ceasing to cut, is superimposed on quartzite in a course exactly coinciding with a peculiar pre-existing filled and buried crooked valley, and then cuts on downward for 900 feet without interruption.

It seems more likely to the writer that the explanation of the reoccupation of the gap by a stream is to be found in the application of the principle of stream adjustment on non-resistant rocks during a cycle of erosion which went nearly to completion. On the 1,400–1,480 foot surface, the streams flowed here on quartzite and there on sandstone. With the uplift of the surface, these streams began to intrench themselves and new tributaries were formed. The larger streams reached grade after cutting 200 feet or so. For most of the streams this downward cutting was through quartzite. The stream which adjusted on the non-resistant sandstone in the gap cut more rapidly than the others, obtaining an advantage in this way; it became a pirate and gradually captured many of the other streams. That there were other streams during this cycle and that they did intrench themselves before being captured is proved by the fact that there are passes or cols across the range at altitudes a little above 1,200 feet, as, for instance, where the West Sauk road crosses the range between the heads of Skillett's Creek and Otter Creek.

At any rate, it was during this cycle of erosion that the Wisconsin or its pre-Glacial ancestor came to flow southward and westward over the present site of the Lower Narrows, up the present course of the Baraboo valley and southward through the shallow Devils Lake gap, and the Baraboo River entered the inclosure between the quartzite ridges through the Upper Narrows, and

joined the Wisconsin at about its point of entrance to Devils Lake gap. The Upper and Lower Narrows may have been formed for the first time by superimposition during the formation of the 1,200-foot plain, or possibly by adjustment of the streams on sandstone, provided they had been made and filled with sandstone.

The age of this lower plain and therefore the date of re-excavation of Devils Lake gap are no more proved than is the age of the upper erosional surface. Those who hold that the upper plain is Cretaceous assign a Tertiary age to the younger plain, and those who believe the upper plain to be Tertiary in age naturally assume that the lower plain was formed at the end of the Tertiary period or early in the Pleistocene. There is some evidence in northeastern Iowa that this plain was intact when the oldest glacial drift was deposited, but this also must be considered to be an open question until more of the field data have been published. At least it is clear that the present Devils Lake gap had its beginnings either in late Tertiary or in early Pleistocene times, which for present purposes is perhaps close enough.

Long before the monadnocks had been removed from this lower plain—that is, before the second cycle of erosion had reached completion—there was another uplift of the land relative to the then existing seas, and the streams were again rejuvenated. This uplift was much greater than the previous one, for the valleys cut during this third cycle of erosion are much deeper than any which were cut during the second cycle. At this time, too, the main part of the present Devils Lake gap was cut. The bottom of the gap at the beginning of this erosion cycle could not have been lower than 1,200 feet A.T. and the tops of the bluffs were no higher than 1,470 feet; that is, the maximum depth of the valley up to the beginning of the last erosion cycle preceding the deposition of the glacial drift was 270 feet. The maximum depth of the valley at the end of this cycle could be determined, if it were possible to get the altitude of bedrock underlying the glacial deposits in the middle of the gap, a bit of information which unfortunately is not available. The deepest boring into the glacial material within the gap was made by Gustaffson and Prader in 1914 at a point near the middle of the gap at the north end of Devils Lake, only a few feet above

lake-level. The altitude of the well-site is about 965 feet. This well penetrates 283 feet of glacial material without striking rock; therefore the bottom of the pre-Glacial gap must be somewhere below 682 feet, and the pre-Glacial gap at this point must have been at least 788 feet deep, at least 500 feet deeper than it was at the end of the second erosion cycle, and at least 283 feet deeper than it is today. The maximum depth of this gap might be known if the altitude of the lowest sub-drift bedrock in the Baraboo valley between the ranges or in the Wisconsin valley south of the South Range could be obtained, assuming that a stream flowed from the Baraboo valley through the gap to the Wisconsin valley to the south. The lowest bedrock surface obtainable in the Baraboo valley east of Baraboo is at 570 feet. Assuming that the bedrock in the Devils Lake gap is as low, the pre-Glacial gap was at least 900 feet deep. It cannot be ascertained whether the pre-Cambrian gap was deeper than this or not so deep, for it cannot be determined whether there are Paleozoic sediments below the bottom of the present gap, nor whether the tops of the ranges were higher then than now. If it be true that the bottom of the pre-Cambrian gap lies at or near 340 feet, the pre-Cambrian gap was probably something like 200 feet deeper than the pre-Glacial gap.

THE GLACIAL LAKE

So far as ascertained, no glacier prior to the Wisconsin glacier affected the Devils Lake gap. There have been some suggestions of pre-Wisconsin drift in the vicinity,[1] but these evidences have proved to be negative. It seems likely, however, that the Illinoian glacier advanced almost to this district; but if it played any part in the history of the lake or its basin, its effects are not now visible within the district.

As has been brought out by Salisbury and Atwood,[2] the Wisconsin glacier formed Devils Lake and had a controlling influence in its early history. As the ice moved into the district from the northeast, it was divided by the ranges, one lobe advancing down the

[1] Samuel Weidman, *Bull. No. 13, Wis. Geol. and Nat. Hist. Surv.*, pp. 99–102.

[2] R. D. Salisbury and W. W. Atwood, *Bull. No. 5, Wis. Geol. and Nat. Hist. Surv.*, pp. 132–33.

old valley of the Wisconsin from the Lower Narrows to the north end of Devils Lake gap, where its edge became stationary and deposited a terminal moraine, the other lobe coming in south of the South Range and advancing up the valley of the pre-Glacial Wisconsin to deposit a marginal ridge across the gap east of its major bend (Plate II). This left the north-south portion of the gap and a part of the east-west portion confined between the two edges of the ice, and in the basin so made Devils Lake was formed. Connecting the ends of the two lobes, the edge of the ice reached its limits of advance in an irregular line crossing the South Range from the north edge of Devils Lake eastward to Sauk Point, and thence southwestward to the gap east of Kirkland (Plate II).

After its formation the lake had an interesting history during the occupancy of the ice.

Sources of supply.—When the lake was first formed, as outlined above, there were at least four separate sources of water supply: (1) The edge of the glacier blocked either end of the lake basin. There the ice melted and furnished water for the basin. Study of the terminal moraine from the north end of the lake around by Sauk Point and southwest to the gap east of Kirkland leads to the conclusion that the water resulting from melting along this whole stretch of ice front must have flowed into Devils Lake basin. (2) The bottom of the basin was below ground-water surface, as evidenced by the fact that it had been occupied by a permanent stream up to the time when this stream was blocked by the ice, and ground water was a source of supply. From the inception of the lake until its bottom was built up above ground-water surface by fluvio-glacial deposition, if this stage was ever reached, some of the lake water may have come from under ground. (3) The lake must have had inlets resulting from precipitation within the borders of the lake basin. For instance, Messenger's Creek with its north and south forks must have flowed into the southwest corner of the lake as it does today, and the stream which flows west and north past the northeast corner of the lake, being blocked to the north by the ice, must have contributed its waters to the lake. (4) There was doubtless direct precipitation upon the surface of the lake. Of these four sources of supply, the first men-

tioned is conceived to be most important, and needs more complete description.

From the extreme east end of the east loop of the terminal moraine at the west foot of Sauk Point, the land slopes south from the north limb of the moraine, north from the south limb, and west from the junction of the two limbs. The water formed by melting at the edge of the ice must therefore have concentrated in the depression between the two limbs of the moraine and must have

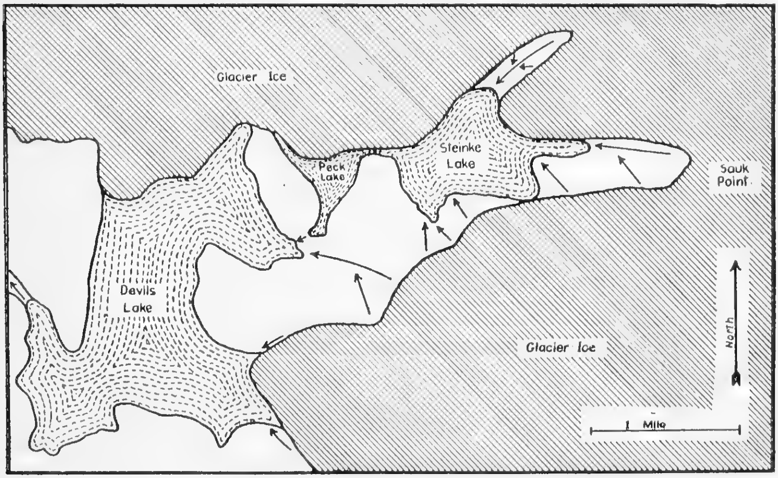


Fig. 1.—Sketch map showing Devils Lake and its drainage basin during the occupancy of the ice.

flowed westward into what has been called the Steinke Lake by Salisbury and Atwood[1] (see Fig. 1). The same general conditions existed in the minor loop north of the Steinke Lake, and the waters from this loop must have mingled with those from Sauk Point in the Steinke Lake.

The Steinke Lake was a body of water about $\frac{3}{4}$ mile long east and west and $\frac{1}{4}$ mile broad north and south, held in by a low ridge of quartzite on the west, the north limb of the ice edge on the north, the westward slope of the land from Sauk Point on the east, and the northward slope of the South Range and the south limb of the

[1] R. D. Salisbury and W. W. Atwood, *Bull. No. 5, Wis. Geol. and Nat. Hist. Surv.*, pp. 120, 133–34, Pl. XXXVII.

ice edge on the south. Short arms or bays projected east toward Sauk Point and north into the narrow loop of the ice edge. As discovered by Salisbury and Atwood, the lowest point in the basin of this extinct lake during the occupancy of the ice, and hence the head of the outlet of the lake, was at the extreme northwest corner of the lake a few rods across the Merrimac Road west of the home of Julius Steinke. The bottom of this outlet is at approximately 1,250 feet A.T., and as the outlet is broad and shallow, it may be assumed that the level of the lake was little if any above 1,260. The water from this lake flowed westward along the front of the ice toward Devils Lake.

The materials now occupying the site of this extinct lake are lacustrine silts, sands, and gravels, finely divided near the middle and coarser around the borders, and coarser at the surface than in the bottoms of deep cuts or borings. The maximum depth of the original lake is not known, but a well on the north side of the flat at the house next west of the schoolhouse, whose site is at 1,260 on lacustrine material, penetrates 202 feet of what appears to be lacustrine material, without reaching rock. This indicates that the original lake was at least 200 feet deep, and that the 200 feet of debris deposited in it was sufficient to fill the lake basin by the time of the retreat of the ice.

From the Steinke Lake the water drained westward into a small pocket or basin having a flat bottom. In late years this little plain has been known locally as the Peck flat. It is an area of perhaps 80 acres, bordering the terminal moraine on the north and sloping gently and getting narrower to the south. On the west, east, and south there are high hills of quartzite, but there is a break in the rim of the basin at its southwest corner, through which drainage is free to flow south and west to the north end of Devils Lake. The width and depth of this valley, the hardness of the quartzite which forms its walls and bottom, and the small size and intermittent character of the stream which drains it, when compared with the post-Glacial valleys of Skillett's Creek and the Wisconsin River, show that this outlet to Peck flat is pre-Glacial. Yet when all available authentic well-records are considered, it is clear that glacial waters could not have flowed at first through this outlet

depression unobstructed. The accompanying table gives the altitudes of well-sites and rock outcrops, depths to sandstone, altitudes of bedrock, etc., for points located in Fig. 2.

TABLE OF WELLS AND OUTCROPS IN THE PECK BASIN

Wells and Outcrops	Altitude of Sight (Feet)	Depth to Sandstone (Feet)	Elevation of Sandstone Surface (Feet)	Depth to Quartzite (Feet)	Elevation of Quartzite Surface (Feet)
Johnson well	1,280	113	1,167	?	?
Peck drilled well	1,225	38	1,187	?	?
Peck dug well	1,220	26+	1,194−	?	?
Iron drill hole	1,210	18	1,192	297+	913−
Marquid well	1,215	6	1,209	121+	1,094−
Steinke sandstone outcrop	1,205	0	1,205	?	?
Steinke quartzite outcrop	1,180	....	....	0	1,180
Steinke well	1,218	6	1,212	155	1,063

From this table and from Fig. 3, it is made clear that the pre-Cambrian surface of this section, as of all portions of the district, was very irregular, and that the post-Paleozoic and pre-Glacial surface sloped north and west from opposite sides of a divide located somewhere near the south end of the present flat.

It is clear that the ice advancing from the north blocked drainage in that direction and melting, furnished water which joined with the discharge from Steinke Lake to make a small lake in the Peck basin. The waters of this lake rose rapidly to the level of the divide at the south end of the basin and overflowed westward into Devils Lake. Peck Lake, shallow from the first, was gradually filled until the lowest point on its bottom was as high as the outlet, and the lake ceased to exist. The filling of the lake must have been accomplished before the retreat of the glacier, for fluvio-glacial material was deposited over the lacustro-glacial material. The Peck dug well (see Fig. 2) penetrates 8 feet of coarse gravel and below that 18 feet of sand. The gravel is fluvio-glacial and the sand below lacustro-glacial. The top of the sand is at 1,212 feet A.T., and this is probably the approximate altitude of the pre-Glacial divide.

From the foregoing it is apparent that all the water from the edge of the glacier in its great complex loop east of Devils Lake flowed into Devils Lake during the occupancy of the ice (see Fig. 1).

The Size of Glacial Devils Lake.—After description of the sources of supply for the basin of Devils Lake during the occupancy of the

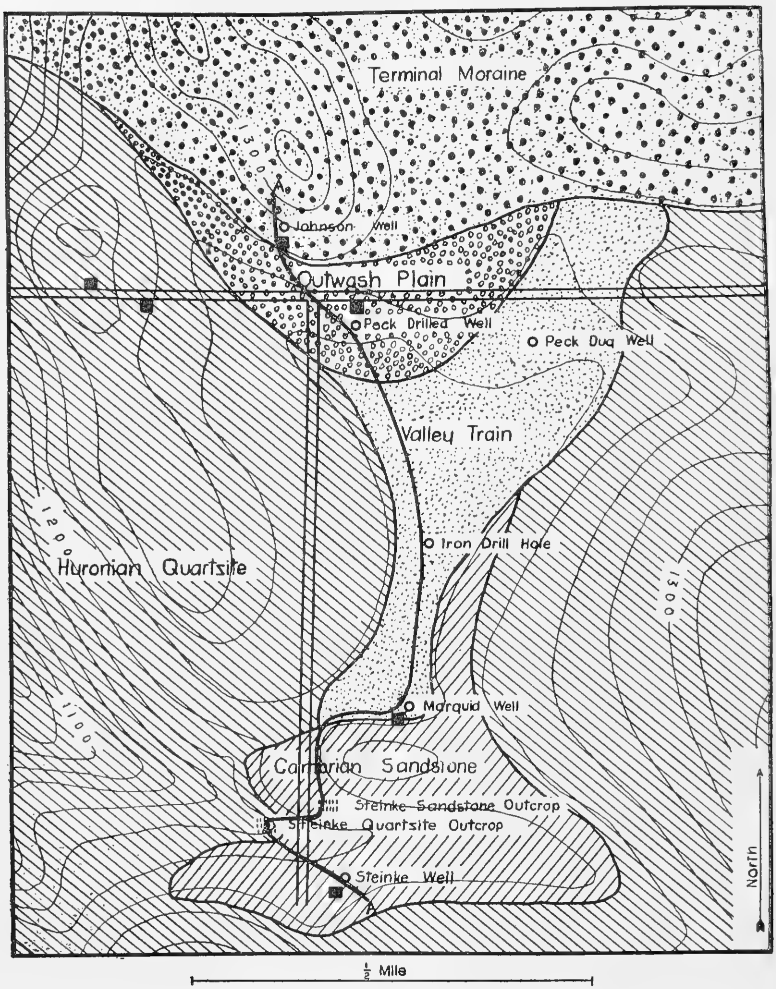


FIG. 2.—A geologic and topographic map of the Peck basin. The locations of wells and outcrops involved in the accompanying table are given, also the line of the section *AA*, shown in Fig. 3.

ice, it is evident that the glacial lake must have been larger than now after most of these sources have been cut off. Indeed, there

is a question as to whether the basin of Devils Lake was large enough to confine all this water. If it be assumed that the amount of water supplied to the basin by ground water was balanced by loss due to seepage into the débris at either end of the lake, and that the precipitation on the surface of the lake and on the lakeward

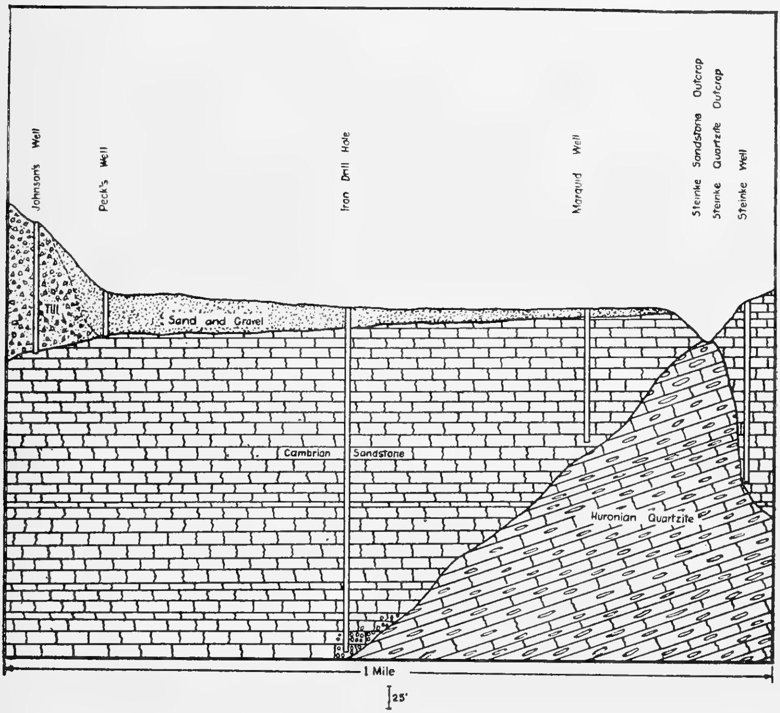


FIG. 3.—Section along line *AA*, Fig. 2, showing surficial and underground conditions in the Peck basin.

slopes was balanced by evaporation, the glacial water is still unaccounted for.

Careful measurement of the terminal moraine from the northwest edge of the Devils Lake basin, through all its curves to the crest of the Devils Nose southeast of the lake, shows that water drained into Devils Lake from 11.6 miles of ice edge. To get some conception of the amount of water which this front of ice contributed, let us suppose that the ice edge tributary to the lake had

an average thickness of 100 feet (probably less than the actual thickness) for the first mile back from its edge. To estimate the total annual water supply from the ice, it is necessary to make reasonable supposition as to the amount of annual melting measured in a horizontal line normal to the front of the ice. The ice front may be considered to have been essentially stationary, and the amount of ice melted can be measured by the rate of glacial motion in the marginal portions of the ice. Chamberlin and Salisbury[1] estimate that the ice in the Greenland glacier moves something less than a foot a week near its edge. Suppose that the glacier which affected Devils Lake moved 6 inches a week or 26 feet a year. If, then, it be assumed that a volume of ice 11.6 miles long measured along the edge of the glacier, 100 feet thick measured vertically, and 26 feet wide measured normally to the ice front, melted each year and ran into Devils Lake, there would be an annual total of about 1½ *billion* cubic feet. The decreased volume due to change from ice to water may be neglected in a computation where there are so many assumptions and where all figures have been reduced to a minimum for safety.

To estimate the capacity of the basin of Devils Lake during the occupancy of the ice, it is necessary to have its length, width, and depth. Measured from moraine to moraine around the curve of the gap, the basin is almost exactly 2 miles long. The average width from end to end and from lake level to lowest point in the rim of the basin is approximately ½ mile. The depth of the glacial lake may be found by subtracting the altitude of the present lake bottom from the altitude of the lowest point in the rim of the basin, neglecting the glacial débris below the bottom of the lake, which would have displaced the water as it was deposited. Computed in this way, the maximum depth of the glacial lake was 270 feet. Multiplying the depth, width, and length, the capacity of the glacial basin was about 7½ *billion* cubic feet.

According to these figures the water from the glacier would have filled the basin of Devils Lake to overflowing in about five years. If the rate of advance of the ice was greater than assumed above

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I, 261.

or if the ice was thicker, and both postulates are reasonable, the time required to fill the basin would have been less.

The foregoing figures may be roughly checked by an estimate of the amount of material deposited by the glacial waters. The 6 miles of ice edge which drained into Steinke Lake furnished water enough to deposit over $2\frac{1}{2}$ *billion* cubic feet *of dêbris;* in the Peck basin water running from $\frac{1}{2}$ mile of ice front deposited at least 142 million cubic feet *of dêbris;* it therefore seems safe to assume that over 11 miles of ice edge furnished over $7\frac{1}{2}$ billion cubic feet *of water.* The Devils Lake gap between the two moraine dams contains over 2 billion cubic feet of débris (10,000 feet in length$\times$1,000 feet in width$\times$283 feet in depth) and most of this must have come in the water from the two short stretches of glacier to the north and southeast, the water from the Steinke and Peck basins doubtless having been essentially clear.

It is not necessary to go farther to warrant the assumption that Devils Lake must have risen during the glacial epoch until it reached an outlet. On the edges of the basin there are only four low points: (1) over the terminal moraine east of the south end of the lake, (2) over or around the west edge of the moraine north of the lake, (3) at the head of the south fork of Messenger's Creek, (4) at the head of the north fork of Messenger's Creek. If the openings to the east and north be considered to have been blocked by the ice, as they doubtless were during the glacial occupancy, the lowest outlet available was between the head of the north fork of Messenger's Creek and the head of a valley tributary to the east fork of Skillett's Creek, where the altitude is between 1,180 and 1,200 feet A.T.

Salisbury and Atwood[1] found evidence that the glacial lake stood 90 feet higher than the present lake, by finding erratic, iceberg-floated bowlders in the talus on the west bluff of the lake at altitudes of 1,050 feet. Theorizing that the lake must have stood even higher than this, that it must have had an outlet, and that icebergs would float toward, and strand in, such an outlet, the writer has made

[1] R. D. Salisbury and W. W. Atwood, *Bull. No. 5, Wis. Geol. and Nat. Hist. Surv.,* p. 133.

careful search for erratic bowlders in the valleys of the north and south forks of Messenger's Creek. An hour's search revealed 103 such bowlders in the valley of the north fork, and an equal time in the valley of the south fork failed to discover one. The highest igneous rock bowlder in the north fork is at 1,162 feet, 202 feet above present lake-level, and only 28 feet lower than the divide across which the lake-water must have drained. Glacial cobbles occur within 16 vertical feet of the divide, and one diabase cobble was found on the west slope of the divide in the drainage of Skillett's Creek.

It is concluded, therefore, that during the Wisconsin epoch the waters of Devils Lake stood against the glacier at the north end, formed a bay up the valley to the northeast about as far as the north-south road in the Peck flat, reached to about the level of Elephant's Rock on the east bluff, stood against the ice at the southeast extremity of the basin, extended to within a short distance of the head of the south fork of Messenger's Creek, and spilled over the divide at the head of the north fork of Messenger's Creek, as shown in Fig. 1 and Fig. 4. Through this outlet the water flowed west into a larger lake, known as the Upper Baraboo Lake, now extinct.

THE POST-GLACIAL LAKE

As the edge of the glacier receded during the closing stages of the Wisconsin glacial epoch, the high level of the lake and its westward-flowing outlet may have been maintained for a time, but when a connection was established between Devils Lake and a lake which came into existence in the Baraboo valley, and whose surface stood at a lower level, the waters of Devils Lake were lowered to the lowest point in the morainic dams. The lowest point on the surface of either moraine was a little east of the middle of the gap at the north end of the lake, along the site of the railroad and wagon road from the lake to Baraboo. The original level of this outlet is not known, because it has now been cut almost to lake-level, but the edges of the outlet gap on the surface of the moraine at either side are at about 1,020 feet, or 60 feet above present lake-level. This is approximately the level of the surface of Devils Lake after the retreat of the ice, and before the outlet had been lowered appreciably.

From the 1,020 foot level (60 feet above the present lake) the lake surface probably was brought down rapidly by the lowering of its outlet. The stream flowing north across the moraine cut its

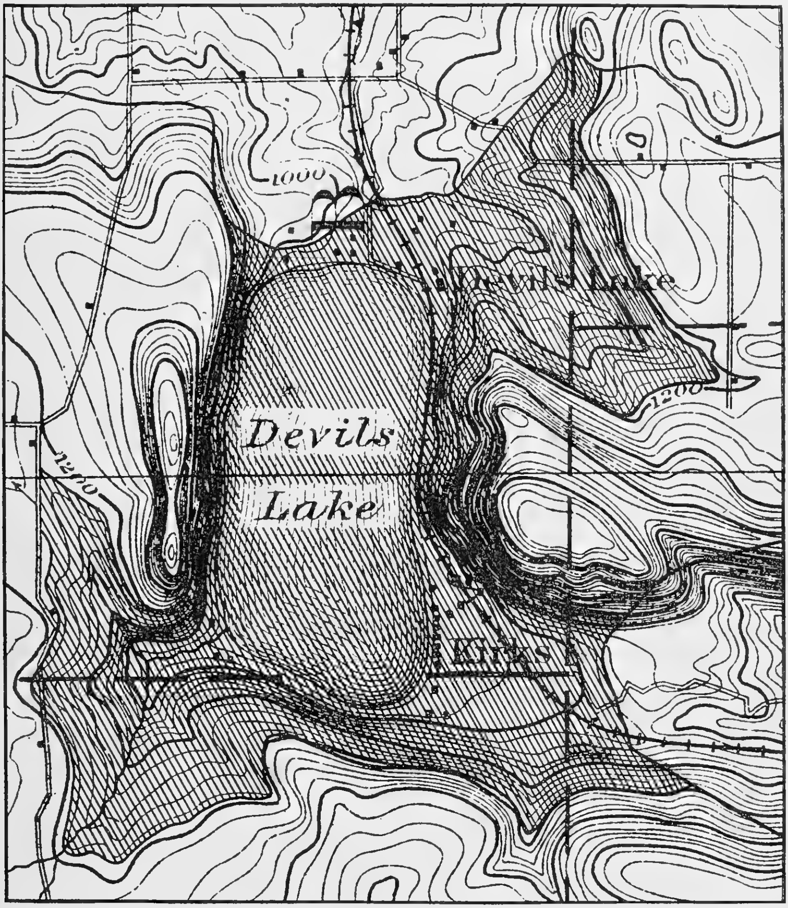


FIG. 4.—A map showing the shape and size of Devils Lake during the occupancy of the ice. The shaded area shows the lake surface. The arrow near the left margin designates the outlet. Scale: $1\frac{5}{8}$ inches equal 1 mile.

way downward in the glacial till, removing the fine material, but leaving the bowlders on its bed, lowering the lake surface from 1,020 to about 970 feet.

The lake surface apparently stood at this level (970 feet) for a time, perhaps because the outlet had made a resistant bed for itself by the accumulation of bowlders on its bottom. The evidence of this stage is a well-defined beach or barrier ridge of sand across the north end of the lake, whose crest is 8–10 feet above the lake and which confines a low, peaty area between it and the moraine. This low area back of the ridge was clearly once a lagoon. The ridge has been so strengthened artificially that it is impossible to tell whether or not it was originally broken at the old outlet, but water which could reach the top of the ridge could today flow north through the old outlet to the Baraboo River.

During this second stage of the lake it is believed still to have been receiving water from the Peck and Steinke basins (though the lakes of these names were extinct) and from a later post-Glacial lake northeast of the Steinke flat, which has become known locally as Shubring Lake. Shubring Lake occupied what is now a flat area, 1 mile by $\frac{1}{3}$ mile in extent, 4 miles northeast of Devils Lake, and just across the terminal moraine from the Steinke flat in the area of ground moraine. The Shubring flat is bordered on the north, west, and south by the inner edge of the terminal moraine and on the east by a drift-covered hill of quartzite. The slopes toward the flat are almost covered in a narrow belt parallel with the edges of the flat by thousands of bowlders which almost form a wall around the old lake bottom and which were concentrated on the shores of the shallow lake by "ice push." This lake was formed as the edge of the ice retreated, leaving an inclosed basin. During the first stages of recession of the ice, the lake received glacial waters, and after the ice had left the confines of the basin precipitation formed the source of supply. The line of outlet of the lake is plainly seen as a flat-bottomed, bowlder-strewn, linear depression interrupting the course of the terminal moraine from the southwest end of the Shubring flat to the Steinke flat south of it, and now used by Mr. Shubring as a roadway across the terminal moraine. The bottom of the valley which was the site of the outlet and the bowlder wall around the lake flat are at the same altitude (hand-level measurement), and not more than 2 feet above the level of the flat. The original depth of the lake is unknown, no records of the depth of the lacustrine fill being available.

It is clear from a study of the post-Glacial drainage conditions east of Devils Lake that the water from Shubring Lake and the Steinke Basin continued to drain into Devils Lake by way of Peck flat for a time at least after the withdrawal of the edge of the ice. These conditions must have persisted until a tributary of the Baraboo River had time to work headward up through the ground moraine on the slope of the South Range and through the terminal

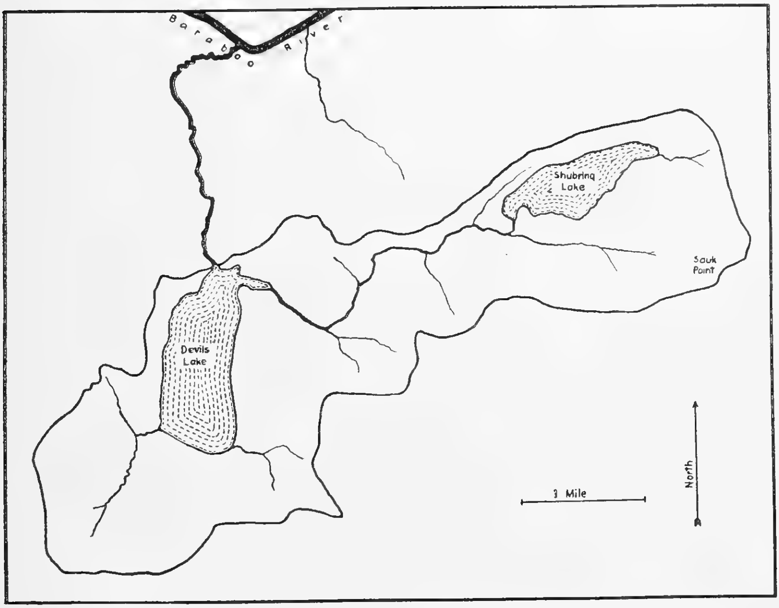


Fig. 5.—Sketch map showing the conditions of drainage around Devils Lake during the first and second stages in the post-Glacial history of the lake. The endless line marks the boundaries of the drainage basin of the lake during these stages.

moraine, to tap the Shubring and Steinke basins and divert their drainage to the north, inaugurating present conditions. The establishment of present drainage would require at least a time commensurate with the time involved in the lowering of the outlet of Devils Lake to the 970-foot level.

So long as Devils Lake had an outlet to the north, that is, until the 970-foot stage was reached, the boundaries of its basin must have been somewhat as shown in Fig. 5.

There remains but one step in the pre-human history of Devils Lake. Its outlet to the north has been abandoned. The reasons for the sinking of the surface of the lake below the level of the outlet may be several. With the gradual establishment of drainage in the ground moraine of the Baraboo valley, a tributary to the Baraboo River worked its way headward up the drift-covered slope of the South Range and through the terminal moraine into the northern

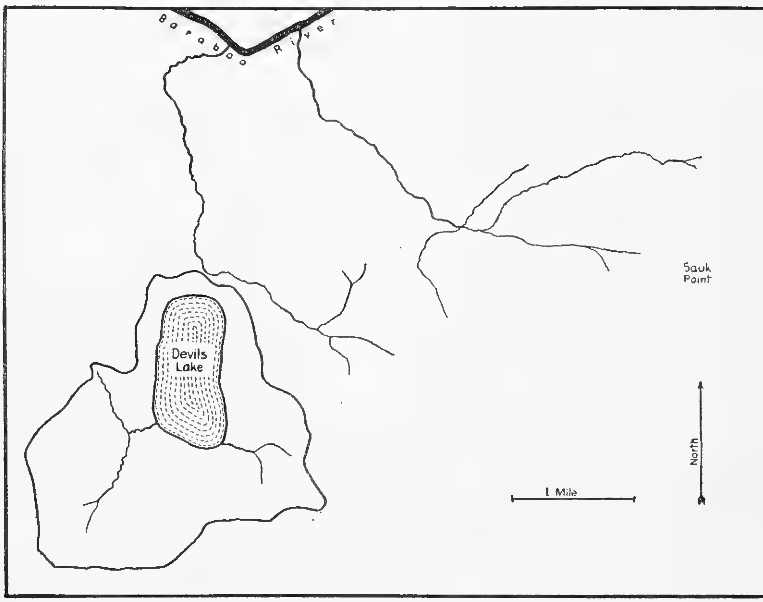


FIG. 6.—Sketch map showing the conditions of drainage around Devils Lake after the diversion of water from the Steinke and Shubring basins and the abandonment of the northward outlet. The endless line marks the boundaries of the drainage basin of Devils Lake.

portion of the Steinke flat, diverting the drainage from the east and northeast, which up to this time had gone to Devils Lake, to Baraboo River. Working rapidly in the non-resistant material of the high Steinke surface, the stream developed a tributary which worked back through the terminal moraine, tapping the Shubring basin west of its original outlet. This diversion of drainage resulted in a considerable decrease in the supply of water for Devils Lake (compare Figs. 5 and 6) and doubtless helped to

cause the lake surface to sink below the level of its outlet. Conceivably also the advance of the post-Glacial epoch was attended by increasing temperature and increasing evaporation and by decreasing precipitation, so that more water was lost by evaporation than was supplied by precipitation. And perhaps the time came when underground lines of drainage were established in the gravel and sand of the drift, through which enough water was carried from the lake to cause its surface to subside. Doubtless all these factors and possibly others contributed to the lowering of the surface of the lake and the abandonment of its outlet.

With the abandonment of the outlet, the stream from the Peck basin, which had flowed into the lake or into its outlet, chose the easier of two possible routes, avoiding the lake and flowing down the valley of the old outlet to Baraboo River. A few years ago, in order to prevent floods in its lower course, this stream was diverted again to Devils Lake by the building of a dam and the digging of a shallow ditch connecting the stream with the lake. Today the stream flows into Baraboo River or into Devils Lake, according as the temporary dam is located in the stream channel or in the artificial ditch.

The lake of today has a maximum depth of only about 40 feet, covers an area of only a little more than $\frac{1}{2}$ square mile, and is without an outlet. Its drainage basin at present is shown in Fig. 6.

SUMMARY

Devils Lake is seen to have had a long and complicated history. (1) Pre-Cambrian rock formations were deposited and folded. (2) Across the edges of the beds a peneplain probably was formed, over which a large stream meandered. (3) An uplift seems to have occurred and the stream intrenched itself, making a deep, curved gorge through a ridge of quartzite. (4) An early Paleozoic sea advanced over a surface of high relief and great irregularity, partially, but not completely, filling the pre-Cambrian gorge with sediments. (5) This sea withdrew at the end of the Prairie du Chien epoch, leaving a sag where the old gorge had been. (6) Conditions favoring deposition in the sea, and perhaps deposition by wind temporarily and locally, were renewed and deposition continued

until the gap was entirely filled and the pre-Paleozoic topography was buried deeply. (7) The seas finally withdrew, stream courses were developed and superimposed upon the old topography and structure, and a peneplain was developed, probably in late Tertiary time. (8) This peneplain was uplifted about 200 feet, and a second partial peneplain was developed. During this erosion cycle the Wisconsin River adjusted itself in the old gorge, and a valley about 300 feet deep was formed. (9) Another uplift to an amount of about 600 feet resulted in renewed erosion and the deepening of the gorge from 300 feet to 900 feet or more. (10) In the northern portion of the renewed gorge so formed, an ice barrier lake was formed by the edge of the Wisconsin glacier blocking the valley at two points. This lake received much glacial water, covered an area twice as large as does the present lake, was at least 270 feet deep, and had an outlet at 1,190 feet A.T., which drained northwestward. (11) With the recession of the ice, the surface of the lake dropped to about 1,020 feet and then to 970 feet, as an outlet to the north was established, and lowered through the terminal moraine dam. (12) Owing to a diversion of drainage in the Steinke and Shubring basins, decreasing the intake, and perhaps owing to changes in climate and the establishment of underground channels, the surface of Devils Lake fell from 970 to 960 feet, and the outlet was abandoned.

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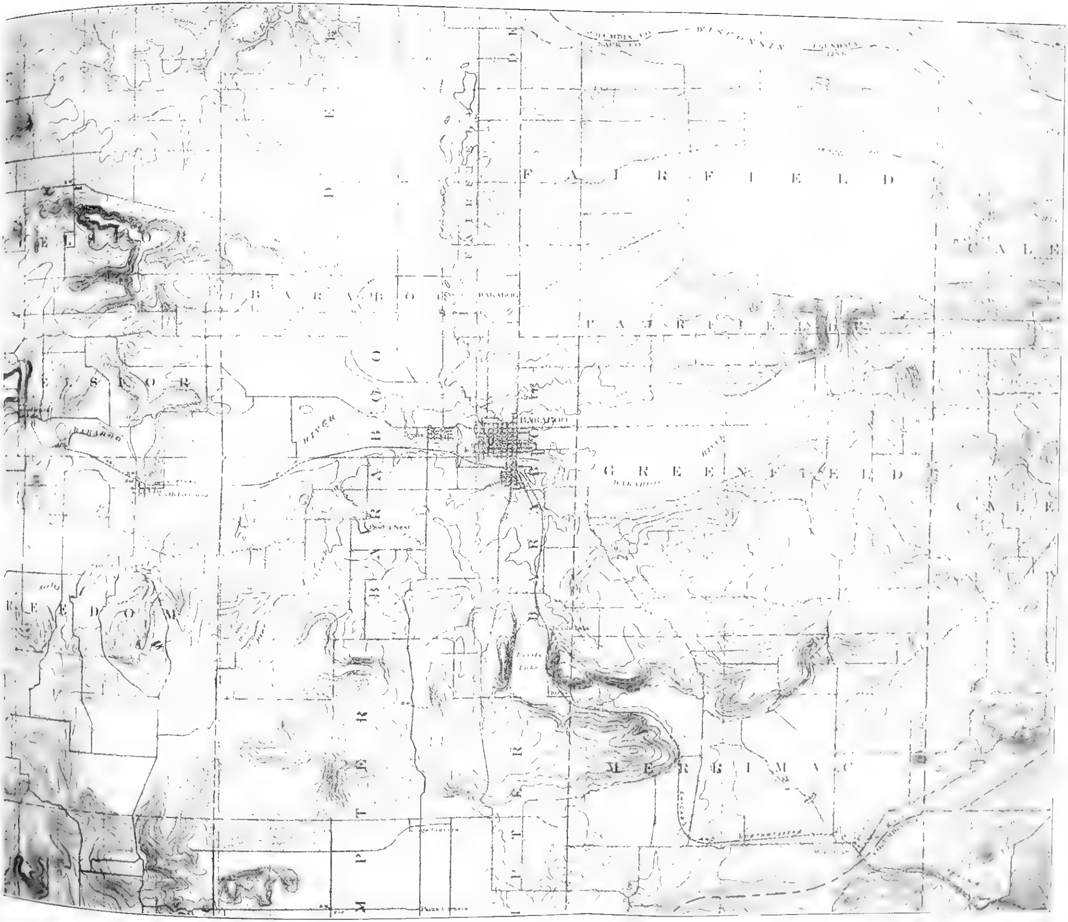
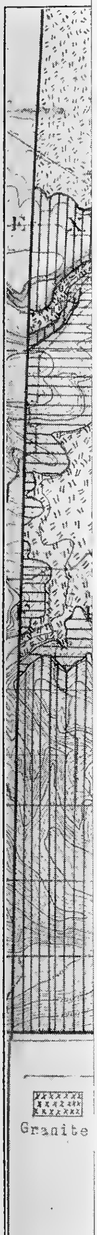
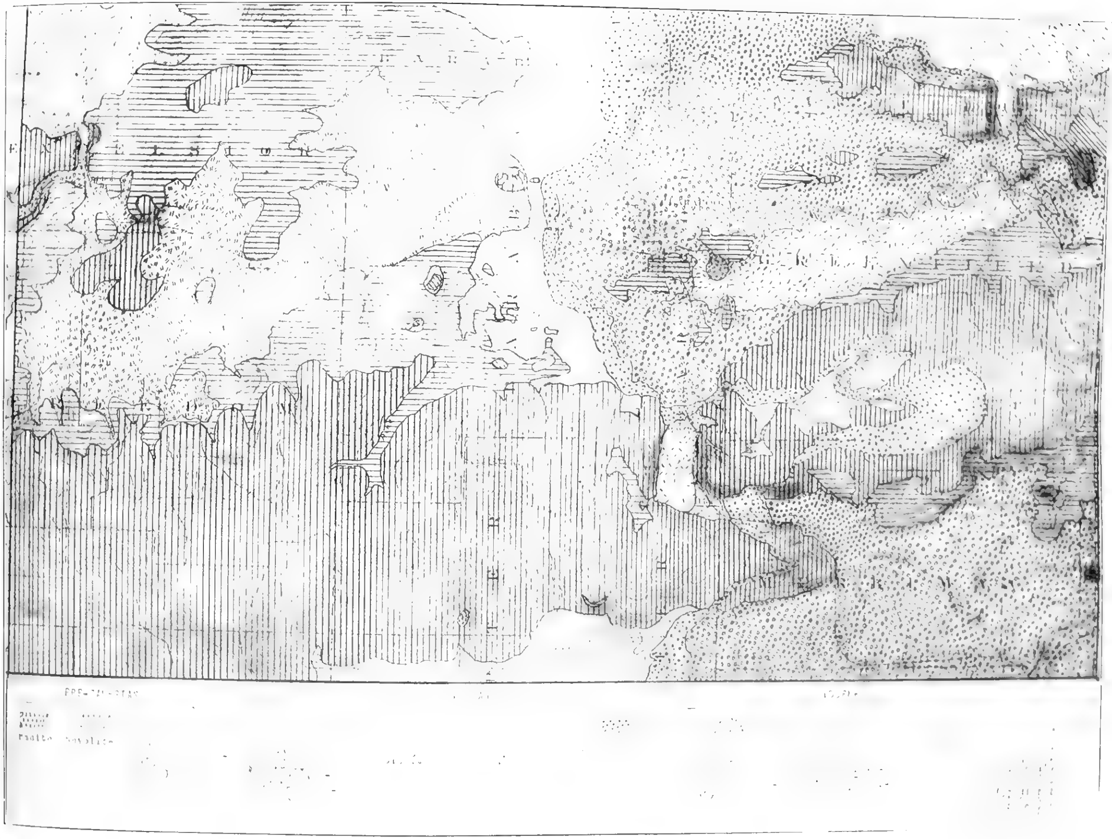


Map Showing the Topographic Setting of Devils Lake

Taken from the Baraboo, Briggsville, Dells, and Denzer sheets of the United States Geological Survey


Granite



Geologic Map of the Vicinity of Deaths Lake

THE MIDDLE PALEOZOIC STRATIGRAPHY OF THE CENTRAL ROCKY MOUNTAIN REGION

C. W. TOMLINSON
University of Chicago

PART III

STRATIGRAPHY—*continued*

THE SILURIAN SYSTEM

In Utah.—This system, not including the Richmond series, is not known with certainty in the central Rocky Mountain region, except in northern Utah, where it was included by Weeks[1] under the name "Paradise limestone," which has been supplanted in official usage by the "Laketown dolomite" of Richardson.[2] Its fauna does not comprise many species, but is ample to demonstrate that the system is Silurian.[3] It is closely allied to the Niagaran faunas of other regions.

In Nevada.—This system may be represented in the upper part of the Lone Mountain limestone of western Nevada, although no diagnostic Silurian fossils have been reported from that formation. The following is an extract from Iddings' section near Modoc Peak, in the Eureka district:

3. Shaly limestone, rich in fossils. Lower part of Nevada limestone.
2. 550 feet. Light-gray siliceous limestone, with fine lines of bedding; in upper portion weathering in almost rectangular fragments; growing less siliceous toward the bottom.
1. 140 feet. Light-gray, highly crystalline, saccharoidal dolomite; not siliceous.[4]

[1] F. B. Weeks, unpublished manuscript, *U.S. Geol. Survey.*

[2] G. B. Richardson, "The Paleozoic Section in Northern Utah," *Amer. Jour. Sci.*, 4th Ser., XXXVI (1913), 406–15.

[3] Cf. E. M. Kindle, "Occurrence of Silurian Faunas in Western America," *Am. Jour. Sci.*, 4th Ser., XXV (1908), 125 ff.

[4] Arnold Hague, *op. cit.*, p. 66. Section measured by J. P. Iddings.

These descriptions show a marked resemblance to the section at Blacksmith Fork, from the lower part of the Jefferson down into the Laketown dolomite.

On the south slope of Quartz Peak in the Pahranagat Range in southern Nevada, about 140 miles south of Eureka, the Lone Mountain includes the following member:

2. 335 feet. Massive bedded dark siliceous limestone, with a stratum (not far above the base) 30 feet thick, almost made up of a species of *Pentamerus*.[1]

This, again, is strikingly like the Laketown.

Is the Laketown dolomite in part Devonian?—The uppermost member of the Laketown dolomite in the Blacksmith Fork section, 202 feet thick, is of much the same type as the Leigh formation of northwestern Wyoming. It immediately underlies beds of typical Jefferson dolomite. In the Teton River section the basal member (23 feet thick) of Blackwelder's[2] Darby (Jefferson) formation is of similar character, and is separated by an erosion surface from the underlying Leigh formation. In the Livingston Peak section there is a member, 21 feet in thickness, which is identical in type with the true Leigh, but which lies above the cliff-making Upper Bighorn dolomite, at the base of the Jefferson dolomite. In the Crandall Creek section the corresponding member, 26 feet thick, overlies a 47-foot sequence of variegated beds which lie disconformably upon the Upper Bighorn. At Livingston Peak and at Teton River, ostracods like those which are characteristic of the Leigh formation were found in this repetition of the Leigh type at the base of the Devonian system.

In brief, the uppermost member of the Laketown dolomite in northern Utah corresponds in lithologic character, and in relation to the overlying Jefferson dolomite, to the member which farther north appears to have been the introductory deposit of the first Devonian submergence. This relation suggests that the Utah member in question belongs with the Devonian rather than with the Silurian system. This interpretation has been followed in the correlation tables and diagrams accompanying this thesis, where the beds just discussed appear as Member 2 of the Devonian system.

[1] Arnold Hague, *op. cit.*, p. 196.

[2] Eliot Blackwelder, unpublished manuscript, *U.S. Geol. Survey*.

Their much greater thickness in Utah may mean that the Devonian submergence proceeded slowly northeastward from that region, or that deposition was more rapid there.

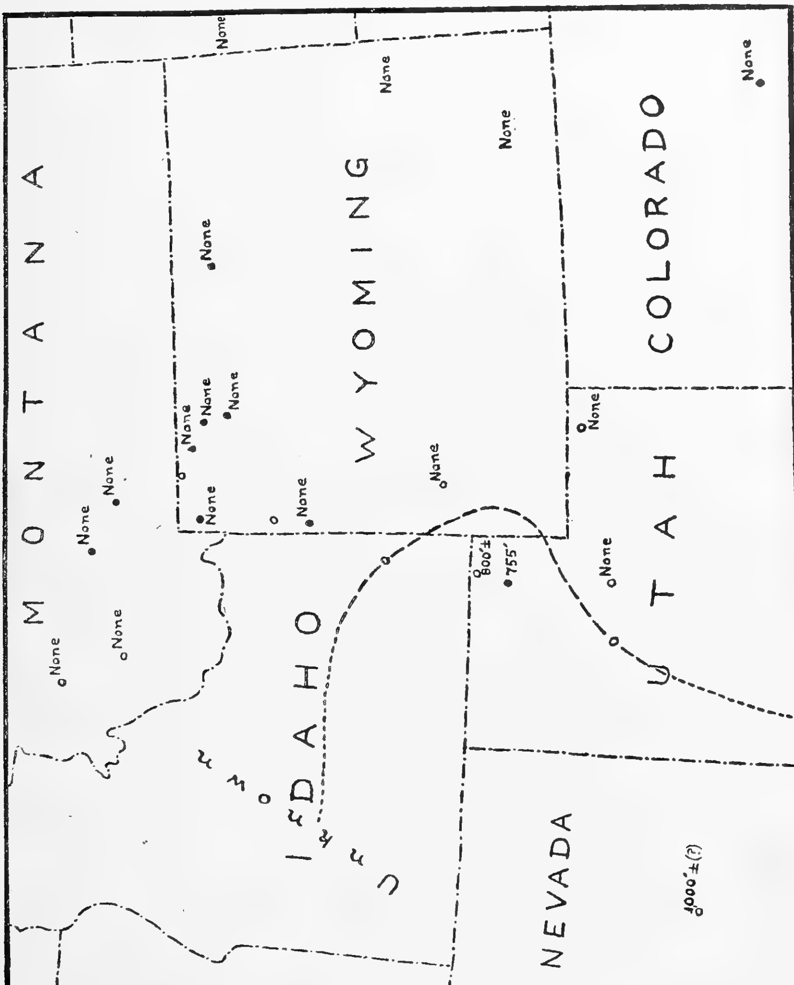


FIG. 9—Map showing the extent and thickness of the Silurian system

Pre-Laketown and pre-Devonian emergence.—The base of the Laketown dolomite at Blacksmith Fork is clearly disconformable upon the Fish Haven formation. No evidence of a break between Silurian and Devonian has been noted in that section; and Kindle,

chiefly because of the persistance of *Halysites catenulatus* into the Jefferson dolomite, favors the idea of continuous sedimentation in this locality from Silurian into Devonian. Elsewhere in the Rocky Mountains, however, where the Silurian is absent, there was certainly an emergent interval immediately preceding the inauguration of Devonian sedimentation. The fact that no physical evidence of hiatus at that time has been noted as yet in northern Utah means little. The recurrence of *Halysites* in the Devonian certainly means no more, as regards continuity of submergence, than its persistence from the Richmond into the Silurian; yet the disconformity between the Richmond and the Silurian on Blacksmith Fork is well marked.

How far the Silurian system originally extended over the Rocky Mountain province can only be conjectured. Throughout Wyoming, wherever the Devonian occurs, it is apparent that the Silurian system, if ever represented, was completely removed by erosion prior to the Devonian submergence.

A small fauna collected by Blackwelder in the Gros Ventre Range from beds just below the Leigh dolomite was referred by Kindle and Weller to the Silurian, and by Ulrich to the Richmond.[1] The latter interpretation is probably correct, as the Leigh of the Teton Range is confidently correlated with part of the Richmond series in the Bighorn Range. Blackwelder's section in the Gros Ventres does not include beds of the types which characterize the Laketown dolomite in Utah.

The Silurian is not represented in Hintze's[2] section in the central Wasatch. The beginning of known Devonian deposition in that region was certainly preceded by an interval of emergence. Neither Silurian nor Devonian strata are known in the Uinta Range.[3]

THE DEVONIAN SYSTEM: THE JEFFERSON DOLOMITE

The basal division of the Jefferson dolomite.—The age of the beds here called Members 1 and 2 of the Devonian system has been discussed under the Silurian. Member 3, which follows 2 in

[1] Eliot Blackwelder, "Origin of the Bighorn Dolomite of Wyoming," *Bull. Geol. Soc. Amer.*, XXIV (1913), 610.

[2] *Op. cit.* [3] F. B. Weeks, *op. cit.*, XVIII (1907), 427–48.

apparent conformity wherever both are present, was the earliest development of the most characteristic Jefferson type of dolomite —dark-brown in color, saccharoidal, and giving forth a strong

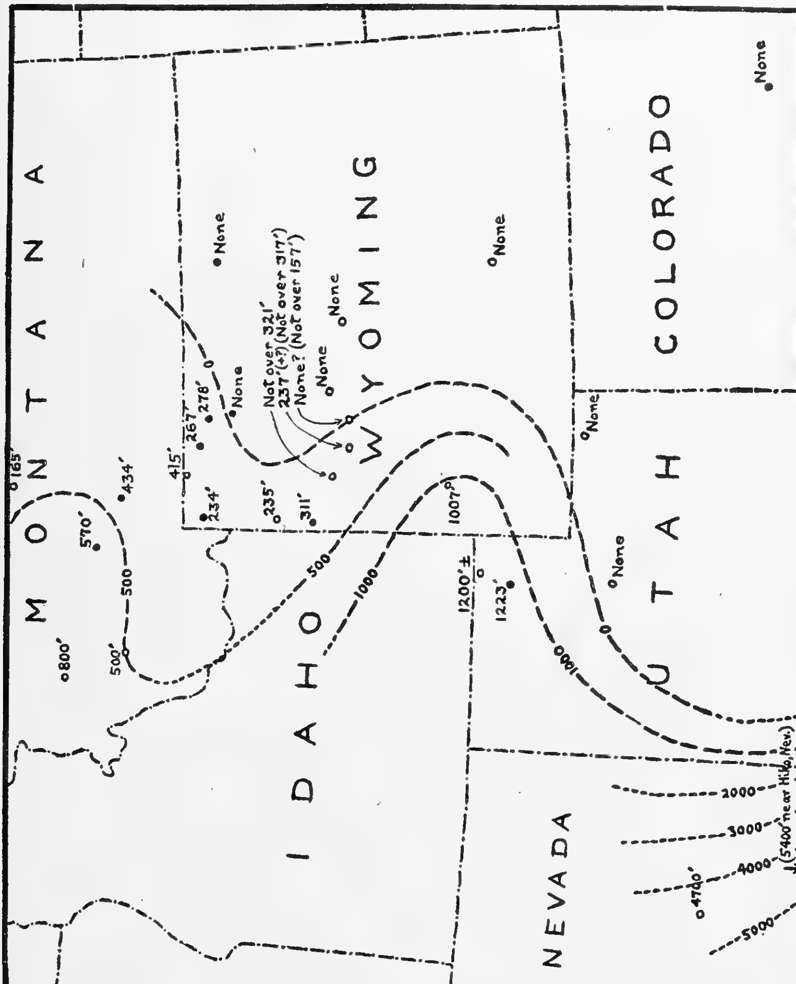


FIG. 10.—Map showing the extent and thickness of the Jefferson dolomite (Lower [?] and Middle Devonian) and correlated formations.

bituminous odor when freshly broken. The data suggesting disconformity at the top of Member 3 are summarized in the discussion of disconformities (pp. 131–34).

The main division of the Jefferson dolomite is dominated by a rather uniform succession of fairly massive, fetid, dark-brown dolomites, but includes toward its base a minor variegated sequence of thin members (4 to 8, inclusive), among which are light-colored dolomite, and locally (Labarge Mountain, Blacksmith Fork) sandstone. The correlation of these minor members on a lithologic basis has been attempted, but cannot be considered very reliable. In no two localities is there the same succession of members throughout the formation, although there is a notable degree of correspondence between the Crandall Creek and Teton River sections, for example. In the Dead Indian Creek, Livingston Peak, Logan, Labarge Mountain, and Blacksmith Fork sections the variegated members are relatively ill-developed, and the outstanding feature of the formation is a nearly uniform sequence, 200 feet thick or more, of what has been described above as the most characteristic Jefferson type of dolomites.

Members 12 to 14 of the Devonian system, above the main body of the Jefferson dolomite, are differentiated only at Blacksmith Fork and at Labarge Mountain, where they have a combined thickness exceeding 200 feet. They appear not to be represented in the sections in northwestern Wyoming and southern Montana. This fact, with certain other evidence, is strongly suggestive of an emergent interval between Members 14 and 15. (See discussion of disconformities, p. 132.)

The upper division of the Jefferson dolomite.—Member 18 is distributed with remarkable uniformity over a very wide area, and has been distinguished in nearly every locality within the scope of this thesis where the Jefferson dolomite has been described in any detail. Its brecciated structure, together with an abundance of calcite geodes in some places, give its weathered surfaces a characteristic nodular, pitted appearance. It is everywhere separated from the main mass of the Jefferson by a sequence of thin-bedded, largely platy dolomites. At Labarge Mountain the base of this sequence is marked by 10 feet of sandstone (Member 15); and in the Teton River section its lower portion contains some thin beds of sandstone, and quartz grains are scattered through several of the beds of dolomite.

This upper division of the Jefferson, as indicated by the correlation diagrams, maintains a fairly constant development even where the main body of the formation beneath it shows much variability.

The beds doubtfully referred to Member 18 in the Goose Creek Ridge and Rattlesnake Mountain sections are not typical of that member, but resemble it in being massive and in underlying a series of thin-bedded dolomites which possess all the essential characters of Member 19. (See discussion of the Three Forks formation, pp. 383–84.) It is perhaps more likely that the beds in question really belong to the Richmond series.

Misuse of the name "Jefferson" in Yellowstone Park and vicinity.—The name "Jefferson" was first used by Peale[1] to describe the dark limestones overlying the Gallatin formation in the Three Forks quadrangle, Montana. The strata included by Peale under that name are now believed to be entirely of Devonian age.[2] As they comprise everything between the Gallatin formation below and the Three Forks shale above in the type locality of the formation, it was natural for other geologists to apply the name "Jefferson" to all the strata between those two formations in neighboring areas. In the Livingston quadrangle,[3] Montana, and in the Absaroka[4] quadrangles, Wyoming, however, Hague confined the name "Jefferson" to the strata which he regarded as Silurian, and extended the name "Three Forks" to include all the limestones carrying Devonian fossils. Iddings and Weed, in Yellowstone Park,[5] employed the names in similar fashion, but not altogether consistently in different parts of the Park.

With the aid of his own field notes, and by as careful a correlation of members as the published descriptions permit, the writer

[1] A. C. Peale, "The Paleozoic Section in the Vicinity of Three Forks, Montana," *U.S. Geol. Survey, Bull. 110* (1895).

[2] E. M. Kindle, letter of March 29, 1916; Edwin Kirk, letter of June 13, 1915.

[3] Arnold Hague, "Description of the Livingston Sheet," *Geol. Atlas U.S.*, Folio 1 (1894).

[4] Arnold Hague, "Description of the Absaroka Quadrangle," *Geol. Atlas U.S.*, Folio 52 (1899).

[5] J. P. Iddings and W. H. Weed, "Descriptive Geology of the Gallatin Mountains," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. i; "Descriptive Geology of the Northern End of the Teton Range," *ibid.*, chap. iv; W. H. Weed, "Geology of the Southern End of the Snowy Range," *ibid.*, chap. vi.

has prepared the accompanying tentative correlation table (Fig. 11) of the sections measured by Iddings and Weed, adding three of his own sections for comparison. The "Jefferson" of Hague, Iddings, and Weed is seen to include the Bighorn dolomite as its chief

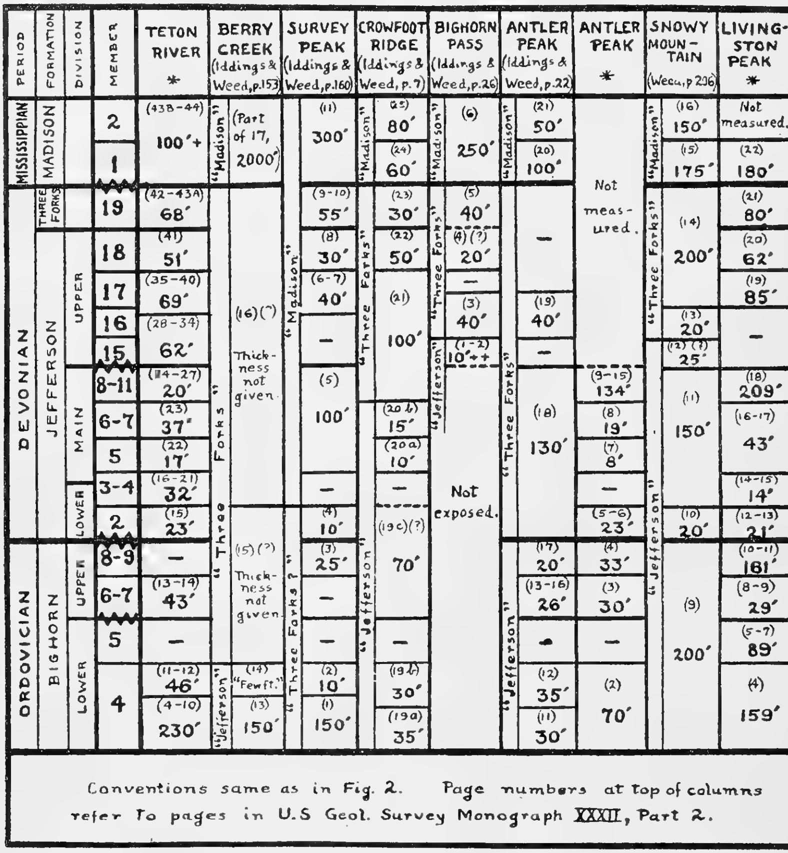


FIG. 11.—Tentative correlation table for sections in Yellowstone Park and vicinity

constituent, and their "Three Forks limestone" consists chiefly of beds which are properly to be correlated with part of the true Jefferson dolomite as originally defined by Peale. The Devonian fossils identified by Girty[1] from Yellowstone Park came from beds

[1] G. R. Girty, "Devonian and Carboniferous Fossils of the Yellowstone National Park," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. xii.

well down in the Jefferson formation, which explains their likeness to the Jefferson fauna known from other regions.[1] The variability of the Three Forks formation from shale to limestone along the strike has been overestimated because of this same erroneous correlation.

Correlation of the Jefferson dolomite with the Nevada limestone.—The Jefferson dolomite, as known in Montana and northern Utah, has been correlated definitely by Kindle[2] with the Nevada limestone of eastern Nevada, on paleontological grounds. Of the eleven specifically identified forms described by Kindle from the Jefferson formation, other than new species, seven were described by Walcott[3] from the Nevada limestone. Of the 32 forms partially or completely identified by Kindle from the Jefferson Limestone, only three are of genera not described by Walcott from Nevada.

The total thickness of the Nevada limestone is estimated by Hague[4] at 6,000 feet. Although accuracy is not claimed for this figure, it cannot be doubted that the Nevada is very much thicker than any described section of the Jefferson limestone. The following figures are given by Hague for the thickness of the Nevada limestone at various localities in the Eureka district:

Newark Mountain[5] (Bed 5): 3,500 feet. Considered by Hague[6] to be less than (the upper) half of the total thickness of the formation. A small Upper Devonian fauna was collected "several hundred feet below the top."

Near Modoc Peak[7] (Beds 3–18): 4,710 feet. (Hague regarded the Nevada as including more than 700 feet of lower strata also.) Rich Lower Devonian fauna in lower 425 feet (Beds 3–4); no fossils other than "*Stromatopora*" and "*Chaetetes*" found at higher horizons.

East of Lamoureux Canyon[8] (Beds 1–5): 3,000 feet, top not exposed. Basal 200 feet carries a rich Lower Devonian fauna.

County Peak:[9] 4,500 feet. Fossils at three horizons.[10]

[1] Cf. E. M. Kindle, "Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bull. Amer. Pal.*, IV, No. 20 (1908), 22.

[2] *Ibid.*, pp. 20–21.

[3] C. D. Walcott, "Paleontology of the Eureka District," *U.S. Geol. Survey, Monographs*, VIII (1884).

[4] Arnold Hague, "Geology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs*, XX (1892), 13, 63–64.

[5] *Ibid.*, pp. 82, 158.

[6] *Ibid.*, p. 158.

[7] *Ibid.*, p. 66.

[8] *Ibid.*, p. 67.

[9] *Ibid.*, p. 68.

[10] *Ibid.*, pp. 78–80.

The occurrence of such great thicknesses at four distinct localities renders it unlikely that the true thickness has been greatly overestimated because of duplication by faulting.

The two chief fossiliferous horizons in the Nevada limestone are near the base and near the top, and are separated by from 2,000 to 4,000 or more feet of strata which have yielded no diagnostic fossils. The fauna described by Kindle from the Jefferson limestone includes 10 forms[1] (2 of which are specifically identified) which occur only in the lower part of the Nevada limestone, 4[2] (3 of which are specifically identified) which occur in both the upper and the lower horizons, and 5[3] (2 of which are specifically identified) which occur in the upper part of the Nevada only. Although this evidence is meager, it suggests that the Jefferson limestone includes representatives of both the basal and upper parts of the Nevada limestone. It is possible that the disconformity between Members 14 and 15 of the Jefferson, for which evidence is cited on page —, represents a large part of the barren middle portion of the Nevada. This would mean that the greater thickness of the Nevada, as compared with the Jefferson, was due, at least in part, to the presence in the Nevada of members which either never were deposited in the Rocky Mountain province or were eroded from that region in Devonian time; that during the Devonian period the eastern part of the Great Basin was more persistently submerged or less elevated in emergent intervals (or both) than was the central Rocky Mountain Region.

In the Pahranagat Range, west of Hiko, in southeastern Nevada, Walcott[4] measured a section including 5,400 feet of strata which he assigned to the Devonian. From this sequence he obtained 22 fossil forms, to 9 of which he assigned definite specific names. All of these forms are identical, according to Walcott's lists, with

[1] *Favosites* sp., *Chonetes* cf. *macrostriata*, *Stropheodonta* sp., *Schuchertella chemungensis*, *Athyris* sp., *Platyceras* sp., *Actinopteria* sp., *Loxonema approximatum?*, *Loxonema nobile*, *Bythocypris?* (*Leperditia?*) sp.

[2] *Stromatopora* sp., *Productella* cf. *spinulicosta* (*Productus subaculeatus*), *Atrypa reticularis*, *Martinia maia*.

[3] *Spirifer utahensis* Meek (*S. disjunctus* Sowerby), *S. engelmanni* Meek, *Pterinopecten* sp., *Naticopsis* sp., *Pleurotomaria* sp.

[4] Arnold Hague, *op. cit. ult.*, pp. 197–99.

species found in the Nevada limestone in the vicinity of Eureka—some in the lower, some in the upper, fossiliferous horizon there.

THE DEVONIAN SYSTEM: THE THREE FORKS FORMATION

Type sections.—As defined by Peale[1] in the type sections in the Three Forks quadrangle, Montana, this formation includes all strata between the top of Member 18 of the Jefferson dolomite and the base of the Madison limestone (Mississippian). Raymond[2] has collected and studied large faunas from several horizons in the type locality opposite Logan. Haynes[3] has carried on Raymond's work, and studied in detail the stratigraphy of the formation in all exposures within about twenty miles of Logan.

Members 19 and 20.—The chief fossiliferous zone of the Three Forks, Member 20 of the Devonian system (Members 4 and 5 of Haynes) has not been identified in Montana east of the Three Forks quadrangle, nor anywhere in Wyoming. It is quite possible that outliers of it may yet be found in those areas, however, as Member 19 is widely distributed there. The top of the Jefferson dolomite is clearly marked in nearly every section in western Wyoming and southwestern Montana by the massive, brecciated Member 18. Were it not for this, the beds of Member 19 might easily be confused with those of Member 17, to which they bear much likeness. In the Dead Indian Creek section, where Member 18 was not recognized, certain strata were assigned to Member 19 because their relation to overlying strata corresponds to the relation of Member 19 to overlying beds in the Crandall Creek section, where Member 18 is present.

Beds of doubtful age in the Bighorn Range, and near Cody.—In the Goose Creek Ridge and Rattlesnake Mountain sections there is a belt of platy buff and yellow dolomites and calcareous shales

[1] A. C. Peale, "The Paleozoic Section in the Vicinity of Three Forks, Montana," *U.S. Geol. Survey, Bull. 110* (1893).

[2] P. E. Raymond, "On the Occurrence in the Rocky Mountains of an Upper Devonian Fauna with *Clymenia*," *Amer. Jour. Sci.*, XXIII (1907), 116–22; "The Fauna of the Upper Devonian of Montana," *Annals of the Carnegie Museum*, V (1909), 141–58; "The *Clymenia* Fauna in the American Devonian," *Proc. Seventh Intern. Zoöl. Cong.* (Boston, 1907).

[3] W. P. Haynes, *op. cit.*, pp. 13–54.

between the top of the fossiliferous Bighorn and the base of the typical Madison, which corresponds closely in lithological character with Member 19 as developed farther northwest. In the Bighorn

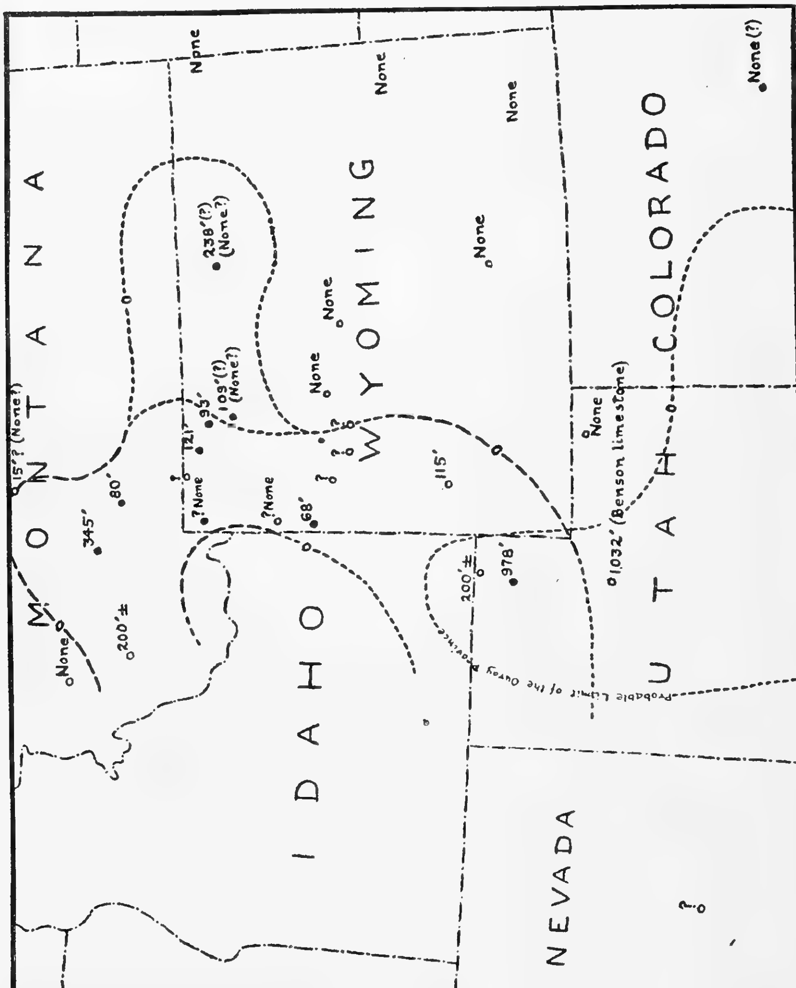


FIG. 12.—Map showing the extent and thickness of the Three Forks (Upper Devonian) and correlated formations.

Range, where this belt is 238 feet thick, it was considered by Darton[1] to be the basal member of the Madison limestone; but it is unlike

[1] N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.*, Folio 141 (1906), p. 4; Goose Creek section.

any part of the true Madison seen by the writer elsewhere. So far as known, it is wholly barren, as is likewise Member 19. It may belong to the Richmond series. However, if the Devonian system is represented in the sections named, it includes this belt, and possibly the underlying massive member which separates it from the fossiliferous Upper Bighorn.

Member 21, comprising black shales overlain by yellow or red aranaceous strata, is found at Crandall Creek and Dead Indian Creek in the Absaroka Range with a development almost precisely like that shown in most of Haynes's sections near Three Forks. Haynes[1] considers that the fauna of this member is transitional to the Mississippian.

The Three Forks formation in northern Utah; correlation with the Benson and Ouray limestones.—Richardson[2] reports very poor exposures of the Three Forks formation in the Randolph quadrangle in northern Utah, with red shaly limestone (Member 19?) as the most conspicuous element in the float. The fauna collected by him from this formation, and identified by Kindle, indicates a mingling of Ouray and Three Forks species. Five[3] of the 7 species in Richardson's list occur also in the Devonian fauna of the Ouray limestone in Colorado,[4] and 6[5] of the 7 occur in the Three Forks formation of the type area.

Haynes[6] has noted the probability of a correlation between the Three Forks and the lower (i.e., the Devonian) part of the Ouray. Of 25 species and varieties of brachiopods listed by Kindle[7] from the latter horizon, and of 27 listed by Haynes[8] from "Bed 5" (part of Member 20 of this paper) of the former, there are 11 which occur in both lists.

[1] *Op. cit.*, pp. 21, 28. [2] *Op. cit.*, p. 412.

[3] *Camarotoechia* cf. *contracta*, *Productella coloradensis*, *Schizophoria striatula* var. *australis*, *Spirifer whitneyi* var. *animasensis*, and *Spirifer notabilis*.

[4] E. M. Kindle, "The Devonian Fauna of the Ouray Limestone," *U.S. Geol. Survey, Bull. 391* (1909).

[5] *C. contracta*, *P. coloradensis*, *S. striatula* var. *australis*, *S. whitneyi* var. *animasensis*, *Syringothyris* cf. *carteri*, *Cleiothyridina* sp.

[6] *Op. cit.*, p. 24.

[7] E. M. Kindle, "The Devonian Fauna of the Ouray Limestones," *U.S. Geol. Survey, Bull. 291* (1909), p. 12.

[8] *Op. cit.*, p. 25.

Richardson[1] estimates the thickness of the Three Forks formation in the Randolph area at 200 feet. In the Blacksmith Fork section both the upper and the lower limits of the Three Forks are marked by the usual sharp lithologic contrasts, yet the strata between the Jefferson and the Madison total 978 feet in thickness. For the most part, this sequence is composed of the usual Three Forks types; but between the green shales below and the black shales above there appears a 360-foot belt of blue-gray limestones (Member 20B).

Less than ten miles south of the above section, in the canyon east of Paradise P.O., Utah, Kindle[2] noted no representative of the Three Forks formation. In the region east of Ogden such a representative is probably to be found, as suggested by Richardson,[3] in the reddish shales and thin-bedded limestones mentioned by Blackwelder,[4] which are 250 feet thick on the South Fork of Ogden River.

In the South Fork of Big Cottonwood Canyon, about 75 miles south of Blacksmith Fork, occurs the Benson limestone of Hintze,[5] comprising 1,032 feet of blue limestone. From a horizon in the upper part of this formation Hintze collected a fauna which is very like that of the Ouray limestone. His description of the Benson indicates that it is lithologically very different from the typical Three Forks. The belt of blue-gray limestones in the middle of the Three Forks formation at Blacksmith Fork, and the upper division of the Jefferson dolomite in the same section, correspond roughly in character with the Benson. This fact, together with the mingled Ouray–Three Forks fauna found in the Randolph quadrangle, suggests the possibility that the Ouray lithologic type dovetails into the Upper Devonian rocks of the more northern and western province.

[1] G. B. Richardson, *op. cit.*, p. 412.

[2] E. M. Kindle, "The Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bull. Amer. Pal.*, IV, No. 20 (1908), 16.

[3] *Op. cit.*, p. 412. Also Eliot Blackwelder, letter of April 29. 1915.

[4] Eliot Blackwelder, "New light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, XXI (1910), 528–29.

[5] F. F. Hintze, Jr., *op. cit.*, pp. 88–142.

SUMMARY OF RESULTS ON SPECIAL PROBLEMS OF INVESTIGATION

The following progress has been made toward the solution of the four special problems noted in the foreword of this thesis:

1. *The Age of the "Jefferson dolomite" in the Livingston, Yellowstone National Park, and Absaroka quadrangles.*—It has been shown beyond doubt that the Ordovician Bighorn dolomite is present, and characteristically developed, throughout the Absaroka Range, as far north as Livingston Peak in Montana, and in Yellowstone Park. It was included in the "Jefferson dolomite" of Hague, Iddings, and Weed. It is followed disconformably by the true Jefferson dolomite (Devonian), much of which was erroneously included by earlier writers under the name "Three Forks formation."

2. *Middle Paleozoic disconformities.*—A well-marked disconformity between the Lower (Trenton) and Upper (Richmond) divisions of the Bighorn dolomite has been discovered in the Absaroka Range. In northwestern Wyoming and southwestern Montana the existence of disconformities at the base of the Bighorn dolomite and at the base of the Jefferson dolomite has been established. Much evidence has been gathered which points toward the existence of disconformities at at least one horizon within the Jefferson dolomite, and at the base of the Mississippian system.

3. *Correlation of Upper Cambrian and Ordovician formations in Wyoming with those in Utah.*—The Upper and Lower divisions of the Fish Haven dolomite in northern Utah have been shown to correspond in lithologic character to the Upper and Lower divisions, respectively, of the Bighorn dolomite; and there is evidence of a disconformity between the two divisions of the Fish Haven dolomite, as well as between those of the Bighorn. Several members of the Gallatin formation of Wyoming and Montana have been tentatively correlated on lithologic grounds with members of the St. Charles formation (Upper Cambrian) in northern Utah, and the main flat-pebble conglomerate zone at the top of the Gallatin is tentatively correlated with a member of similar character in Utah which includes the top of the St. Charles formation and the lower part of the Garden City (Beekmantown) formation.

4. *Relation of Ordovician to Silurian in Utah.*—In the vicinity of Blacksmith Fork, northern Utah, the Laketown dolomite (Silurian) has been found to be separated from the underlying Upper Fish Haven dolomite (Richmond) by a well-marked disconformity.

HISTORICAL SKETCH

UPPER CAMBRIAN AND LOWER ORDOVICIAN

Extent of submergence.—The present extent and variations in thickness of the sediments deposited in the central Rocky Mountain region during the Upper Cambrian-Lower Ordovician submergence are shown in Fig. 7. It will be noted that this is not a paleogeographic map in the usual sense, as no attempt has been made to indicate the original extent of these sediments, other than to show them as continuous across relatively small areas, from which they have certainly been removed by post-Cretaceous erosion.

The much greater thickness of this group of sediments in western and northern Utah and in Nevada, as compared with Wyoming and Montana, means either that (1) sedimentation continued longer or (2) took place more rapidly in the first-named region, or that (3) during the succeeding interval of emergence erosion removed a larger part of the series in question from Wyoming and Montana than from the adjoining region to the southwest. Certainly the first and last, and perhaps all three, of these factors combined to produce the net result. A logical supposition is that the sea retreated from northeast to southwest, so that deposition continued in the Great Basin after erosion had begun on recently emerged areas in Wyoming and Montana. The wide-spread uniformity in type of the sediments in question indicates a similarly extensive uniformity of conditions of deposition, and suggests that the second factor was not of great importance.

Paucity of clastic sediments.—The beginning of the Upper Cambrian transgression in Utah was marked by a deposit of sand of varying thickness. From that time until the close of the Beekmantown epoch no part of the region in which the St. Charles, Garden City, Gallatin, and Upper Deadwood formations are found

received any notable quantity of arenaceous sediment, so far as the record now shows. During long intervals the deposits accumulating on the floor of the clear sea which covered this area were nearly or quite without clastic ingredients. At no time was clastic mud brought in in such quantity as greatly to preponderate over calcareous matter. This condition makes it certain that there were no high shores, nor debouchures of streams draining areas of high relief or dry climate, in or very near to the region under consideration.

Evidence that the sea was shallow.—The intraformational conglomerates which characterize the upper part of the Upper Cambrian and much of the Beekmantown series record the fact that the seas of that time were shallow enough to permit the breaking and movement, by waves or currents, of freshly or partly consolidated sediments on the sea bottom.

The Chazyan(?) sands.—Somewhat later in the Ordovician period, probably in the Chazyan epoch, a flood of sand swept over the extreme northern part of Utah and much of eastern Nevada (see Fig. 8). This was probably the result of an uplift of neighboring lands, perhaps in central or eastern Utah.

Emergence and peneplanation.—Subsequently, the entire region shown in the accompanying maps (Figs. 6–10, 12, 13) emerged and the freshly exposed sediments were subjected to extensive erosion, which continued until about the close of the Black River epoch. This emergence took place without any appreciable deformation of the Cambrian and early Ordovician sediments. Probably it produced no great relief in the region where those sediments are known. The first deposits of the succeeding submergence were laid down on a surface whose relief probably did not exceed 200 feet in all northern and western Wyoming, and on which, in that region, slopes as steep as 10° were, so far as known, nowhere more than a few feet or yards in length. Either the relief was not greater than this at any time during the interval of emergence or a rougher surface was reduced to this condition by stream erosion during that interval, with the aid of marine planation at the border of the advancing Middle Ordovician sea.

MIDDLE AND UPPER ORDOVICIAN

The Trenton submergence.—About the end of Black River time the sea readvanced into the central Rocky Mountain region, probably from the west. The area known to have been covered by this inundation in Utah and Wyoming is approximately the same as in the case of the Late Cambrian submergence (see Fig. 9). Locally, in Wyoming a little sand was deposited in depressions of the surface as the sea-border transgressed the region; but the main body of limestone which represents this Trenton submergence is wholly free from arenaceous and shaly matter. The seas were even more persistently clear than in Upper Cambrian time.

The masses of calcareous algæ which make up much of the Lower Bighorn and Lower Fish Haven dolomites bear witness to the prevalent shallowness of the water.

The post-Trenton emergence.—Sedimentation was interrupted by emergence between Trenton and Richmond times, but the erosion accomplished during this interval seems to have been slight. If any considerable thickness of strata was removed at this time, no remnants of them have been recognized. It is probable that the land was not uplifted much above the base level of the streams which drained its surface.

The Richmond submergence.—With the return of the sea in the Richmond epoch the processes of deposition were resumed under conditions similar to those which obtained during the Trenton epoch. The seas remained clear until the end of the Ordovician record. As in the case of the Upper Cambrian formations, the Bighorn and Fish Haven dolomites present no evidence, aside from the sandstone locally found at the base of the Bighorn, of proximity to shore lines. The original extent of the Bighorn formation was probably much greater than the area in which it now is found. The long period of emergence which followed its deposition afforded ample opportunity for erosion.

SILURIAN

Emergence.—During the early part of the Silurian period (Medina and Clinton epochs) the entire central Rocky Mountain region was above sea. The emergence, like the two or three next

preceding ones, was accomplished, so far as the known record shows, without crustal deformation. In Wyoming, Montana, and Colorado, this interval of emergence may have continued without interruption until Devonian time.

The Niagaran(?) invasion.—Toward the middle of the period, probably in the Niagaran epoch, the sea invaded this region again, from the Great Basin side. The sediments deposited in this sea are known only in northern Utah (and in Nevada?), but may once have been far more extensive (see Fig. 10). The *Conchidium knighti* fauna found in the Laketown dolomite implies a marine connection with Alaska and with Europe.

DEVONIAN

Pre-Jefferson erosion.—The Jefferson dolomite overlaps far beyond the Laketown dolomite into western Wyoming and southwestern Montana. In Wyoming it rests upon various horizons of the Upper Bighorn dolomite. In Montana, north and west of Livingston, it lies directly upon the Upper Cambrian. It is probable that the Bighorn dolomite once extended farther into Montana, and was removed by pre-Jefferson erosion. If the Silurian system originally extended into Wyoming or Montana, it also must have been removed at this time. In Utah, no evidence of a hiatus between the Silurian and the Devonian has been noted.

Although the Jefferson dolomite overlaps both the Silurian and the Ordovician systems, the surface upon which the first sediments of the Jefferson dolomite were deposited appears to have been almost as level as that on which the Lower Bighorn dolomite was laid down. A suggestion of relief is furnished by the contrast between the sections at Logan and Livingston, Montana. Near Logan, the Jefferson rests upon Member 3 of the Cambrian system. At Livingston Peak, about 50 miles to the east, 438 feet of Bighorn dolomite intervene between the Jefferson and that member. Even this difference indicates but an inappreciable slope.

Devonian marine invasions.—The Devonian submergence, during which the Jefferson dolomite was deposited, was probably interrupted in Wyoming and Montana by at least one interval of emergence. The sea appears to have made two or three successive

advances from Nevada northeastward, so that the thickness of its deposits diminishes toward the northeast because of both a progressively shorter total duration of sedimentation in that direction and, correspondingly, a progressively longer duration of the intervening emergences, with accompanying erosion. A small amount of sand, diminishing toward the northeast, was deposited in the shoreward portion of the sea during each advance. Aside from this, little or no clastic material was laid down in the Devonian sea in the central Rocky Mountain region until the later part of the period.

The Upper Devonian muds.—In the Upper Devonian the calcareous sediments accumulating on the sea bottom in Utah, Wyoming, and Montana (see Fig. 12) were polluted by an influx of mud, which in Utah attained a thickness of several hundred feet. The Three Forks formation comprises the resulting shales and limestones, together with a small thickness of arenaceous sediments, only locally present, which may date from the beginning of the Mississippian submergence rather than from the close of the Devonian. The sea which occupied parts of Colorado and central Utah in Upper Devonian time seems to have been connected directly with the Three Forks sea for a short time only, near the middle of the epoch.

THE PRE-MISSISSIPPIAN INTERVAL OF EMERGENCE

Depth of erosion.—It is certain that all of Wyoming, most of Montana, and much of Colorado was above sea-level and undergoing erosion at the close of the Devonian period. The Lower Mississippian sediments (Madison limestone) overlap all older Paleozoic formations (see Fig. 13). The gradual truncation of the Bighorn dolomite and the upper part of the Deadwood formation by the Madison limestone in the southern part of the Bighorn Range is clearly due to pre-Mississippian erosion, and the varying thickness of the Three Forks formation in northwestern Wyoming and part of southwestern Montana is due to the same cause. The relief of the final surface on which the Madison limestone rests, however, is nowhere very pronounced.

Where the Mississippian strata rest upon Ordovician rocks a part of the hiatus may be attributed to erosion during Silurian and

early Devonian time; and where they lie on the Cambrian, the pre-Bighorn emergence also must be reckoned with. Again, it is probable that parts of the region never were covered by strata of the

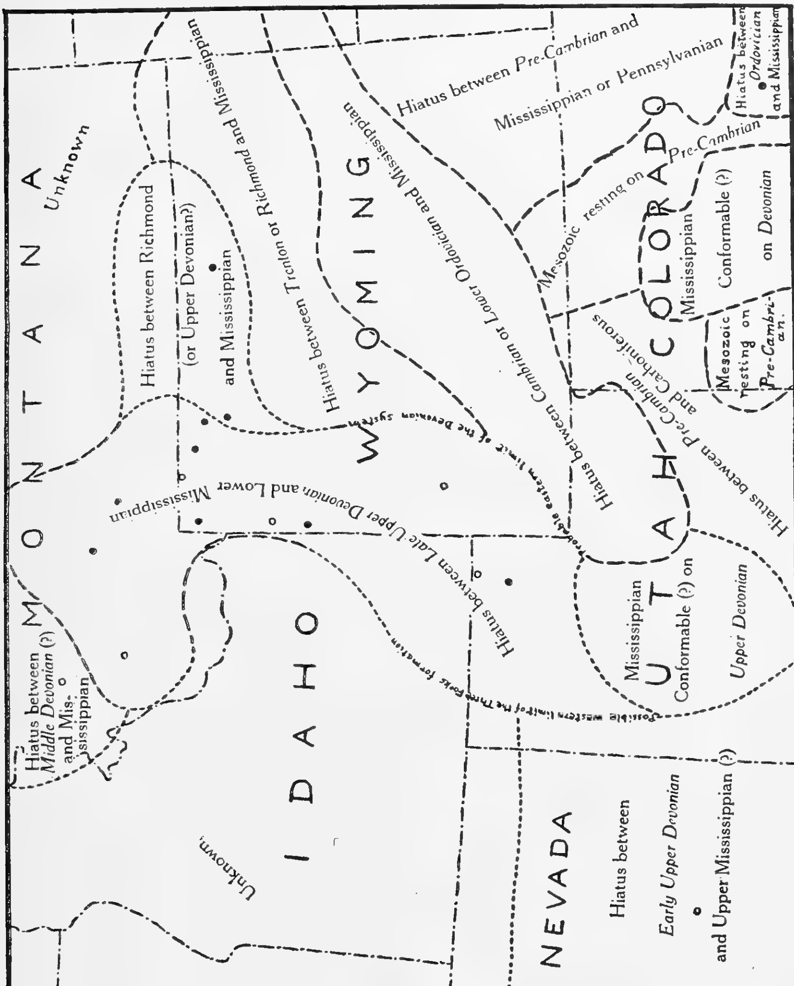


FIG. 13.—Map showing the length of the pre-Mississippian hiatus in the central Rocky Mountain region

age of some of the formations which appear elsewhere. The extreme view, that none of the existing Middle Paleozoic formations ever extended much beyond their present limits, is certainly not true in the central Rocky Mountain region. The other extreme,

that every one of them once extended over the whole area and was cut back by erosion before the Mississippian period, is likewise, in all probability, incorrect.

"Positive" and "Negative" areas; axes of warping.—Whatever was the true proportion between erosion and non-deposition, the net result is shown in Fig. 13, which is, in effect, a paleo*geologic* map of the central Rocky Mountain region at the close of the pre-Mississippian interval of emergence. If the area of Cambrian and pre-Cambrian rocks which then extended from eastern Utah northeastward across southern Wyoming and northern Colorado owed its exposure to the erosion of Middle Paleozoic formations during emergent intervals, it certainly was more exposed to erosion during those intervals than were the adjacent areas on either side of it—probably because of greater altitude. If its exposure was due wholly to non-deposition of the Middle Paleozoic formations, then it must have been above water when neighboring areas were submerged. In either case, or under any hypothesis which combines the two views, *this area of Cambrian and pre-Cambrian rocks must have been at a greater average altitude* during Middle Paleozoic time than the areas on either side of it.

The major axis of this area of upward tendency is approximately at right angles to the average trend of the Rocky Mountain folds. The downward-tending belt, which is known to have been covered by most of the Middle Paleozoic seas, extends in parallel fashion from the northern part of the Great Basin northeastward across the Rocky Mountain province. This is well illustrated by the distribution of the Bighorn dolomite (see Fig. 9).

The trend of these belts indicates the direction of axes of warping merely, not of true orogeny.

The pre-Mississippian interval of emergence was brought to a close by an invasion of the sea, whose deposits are more widespread in the central Rocky Mountain region than are those of any preceding submergence.

Reviews

Mineral Deposits of the Santa Rita and Patagonia Mountains, Arizona. By Frank C. Schrader, with contributions by James M. Hill. U.S. Geol. Survey, Bull. 582, 1915. Pp. 373, pls. 25.

This report covers an area of some 1,400 square miles extending north and east from the city of Nogales, Arizona, on the Mexican border. The mountain groups are short, irregular ranges bordered by broad, sloping plains of Quaternary gravels. Mesozoic granite, quartz diorite, and quartz monzonite, granite porphyry and aplite, with Tertiary andesite, rhyolite, and bedded tuffs and agglomerates, constitute the two groups of igneous rocks which outcrop over about two-thirds of the mountainous area. The remaining third is occupied by a thick sequence of Cretaceous (?) shales unconformably underlain by Carboniferous and Devonian limestones and older shales and quartzites.

The chief mineralization in this area accompanied or followed the Mesozoic intrusions. Silver, copper, gold, and lead are the leading metals. Fissure veins, contact-metamorphic deposits, replacement deposits, and gold placers are all of notable importance. Copper is the most important metal in the contact deposits, while silver and lead dominate in the replacement type, which is here rather carefully distinguished from the contact deposits proper. The average depth of ground-water level and of the oxide zone is about 250 feet.

C. W. T.

Some Mining Districts in Northeastern California and Northwestern Nevada. By James M. Hill. U.S. Geol. Survey, Bull. 594, 1915. Pp. 196, pls. 12.

This is a report on a reconnaissance of nineteen widely scattered mining districts below first rank in present-day importance, sixteen of them in Nevada and three in California The chief value of the work will be to those who are specially interested in the development of one or more of these districts, though a number of points of general interest in economic geology are brought out.

Gold-silver, silver-lead, copper, and antimony deposits are described. Two epochs of mineralization are recognized, the first following the intrusion of a group of granitoid rocks in late Cretaceous or early Tertiary time, the second following the extrusion of a group of later Tertiary andesites and rhyolites. Most of the ores are believed to date from the former epoch. The gold-silver and silver-lead ores are vein deposits. Most of the copper ores are replacements of sedimentary rocks in the vicinity of monzonitic intrusives.

A number of good examples of magmatic differentiation are described.

C. W. T.

"A Geologic Reconnaissance of the Cuzco Valley, Peru." By HERBERT E. GREGORY. *Am. Jour. Sci.*, XLI (1916), pp. 1–100, pls. 2, figs. 44. Contributions from the Peruvian Expedition of 1912 under the Auspices of Yale University and the National Geographic Society.

The bottom of Cuzco Valley ranges from 10,000 to 11,000 feet above the sea. The higher peaks of its bordering ranges reach heights of from 14,000 to nearly 16,000 feet. Between 13,000 and 13,500 feet above the sea, there is a well-defined plateau surface, called by Gregory the "Inca peneplain." It is characterized by much gentler slopes than those of the deep canyons which have been incised into it by the present streams. It is underlain for the most part by complexly folded and faulted sedimentary rocks. Quaternary glaciation molded all of this region above 13,500 feet, and occasional moraines descend to 12,500 feet.

The Cuzco Basin, occupying the upper end of the valley, is about ten miles long by three miles wide. It is believed to owe its origin to faulting. It is floored with lacustrine sediments, probably of pre-glacial age, which are overlapped by large alluvial fans, now being dissected. At the head of the valley is a plateau surface sloping from 11,500 feet up to 13,000 feet above sea-level, underlain by Cretaceous limestones carrying marine fossils—the only marine sediments known in this region. The great bulk of the mountain masses surrounding the valley is made up of clastic sedimentary rocks: brown sandstones, chocolate shales, and conglomerates. These are divided by Gregory into three formations, one of which is composed chiefly of pyroclastic material. They are tentatively assigned to the Permian and Jura-Trias. There

are also mapped several bodies of intrusive diorite and syenite, and small areas of andesitic and basaltic lavas, all doubtfully assigned to the Tertiary.

C. W. T.

Boone County. By C. E. Krebs and D. D. Teets, Jr. West Virginia Geol. Survey, 1915. Pp. 648, pls. 52, figs. 3, maps 2.

County reports now published cover the greater part of the northern and western sections of the state. In these reports are chapters on physiography and mineral resources, but those treating of the stratigraphy of the area are of more general interest.

In Boone County the outcropping rocks range in age from the middle of the Conemaugh to near the base of the Kanawha series. The Kanawha has a remarkable development. It has been differentiated into 29 formations totaling 1,844 feet in thickness. About 30 coal beds from 1 to 15 feet thick are intercalated in the series. Scores of partial sections are given.

There is a preliminary report on the paleontology of the county, and an excellent geologic map accompanies the report in a separate cover.

W. B. W.

Guidebook of the Western United States. Part B, The Overland Route. By W. T. Lee, R. W. Stone, H. S. Gale, and Others. U.S. Geol. Survey, Bull. 612, 1915. Pp. 244, pls. 50, figs. 20, maps 25.

This series of guidebooks is without question the best ever published and should find a wide use among the traveling public of the United States. This volume serves at once to direct the attention of the traveler to the things most worth observing in the land through which he passes, and to render more interesting every stage of the journey. Even the best-informed person, who has been over the route many times, cannot fail to profit by the use of it, and those planning a trip for the first time will find in it by far the most complete, reliable, and attractively written guide available. A wealth of historical, geographical, and geological information is woven together into an interesting and comprehensive whole, written in narrative style. The industries and agricultural and mineral resources of the regions passed through are discussed, and a few

appropriate statistics are given. Withal, the book is not too long to be easily read in the course of the journey.

Although technical terms are consistently avoided, with the exception of a few essential ones which are explained in a brief glossary, a large amount of geological information of general interest is included. The numerous photographs are exceptionally well chosen, and well adapted to awaken interest in geology. There are 25 admirable maps on a scale of 1:500,000, showing topographic, geologic, and cultural features, and mounted in a manner convenient for the reader.

This bulletin covers the route followed by the Union Pacific from Omaha to Ogden, that of the Southern Pacific from Ogden to San Francisco, and that of the Oregon Short Line from Ogden to Yellowstone National Park. It is obtainable from the Superintendent of Documents, Washington, D.C., for fifty cents, postage free.

C. W. T.

Gold on the North Saskatchewan River. By J. B. Tyrrell. Canadian Mining Inst., Toronto, 1915, pp. 68–81.

Summarizes the general geology of the region, and describes the occurrence of gold in the gravels of the stream. The gold is said to be most abundant from Goose Encampment to Beaver Lake Creek, a distance of 130 miles. Some gold has been recovered from gravel taken out for use on the streets of Edmonton.

A. D. B.

Die mikroscopische Untersuchung der Erzlagerstätten. By Georg Berg. Berlin, 1915. Pp. 198, figs. 88.

A book for use in the laboratory. The work is divided into four parts, as follows: (I) optical and microchemical methods, covering opaque and transparent minerals, reactions for the identification of compounds and elements, chemically and by means of *anlauf farben;* an appendix deals with manipulation, separation, and preparation of material, etc.; (II) microscopic characters of the more important ore and gangue minerals; in this section the minerals discussed are grouped according to crystal system; in addition to their appearance under the microscope, the more important physical characters are given. Associated minerals are usually mentioned; (III) the microscopic structure on the important types of ore deposits; a large number of figures illustrate typical sections of the various kinds of deposits; the grouping is

genetic and mineralogic; (IV) petrography of the thermally and pneumatolytically altered rocks.

The work should be of great value, as it is the most complete that has come to the reviewer's hands, and the field is one of great and growing importance. As a pioneer work it will doubtless need additions in the near future, but for the present it fills a long-felt want.

A. D. B.

Mineral Resources of New Mexico. By FAYETTE A. JONES. Bull. 1, State School of Mines Mineral Resources Survey of New Mexico. Socorro, 1915. Pp. 77, map 1.

A catalogue of the various mineral products that the state is thought to be capable of producing. The entire lack of statistics of production detracts from the value of the book, and the potential possibilities of the state in the matter of resources not now being exploited is left largely to the optimism of the reader.

A. D. B.

A Gold-Platinum-Palladium Lode in Southern Nevada. By ADOLPH KNOPF. U.S. Geol. Survey, Bull. 260-A. Washington, 1915. Pp. 18, pl. 1.

Describes briefly the occurrence of a gold-platinum-palladium vein in dolomite in the Boss mine in the southern point of Nevada. The claim was first worked for copper, as the gold, occurring in black particles, was not readily recognizable as such. The veins are strongly oxidized and present development does not reveal conclusive evidence as to the origin or the original mineralogical character of the vein. The deposit apparently adds a new type to the list of American ore deposits. Values up to Pt. 99 oz., Au. 111 oz., and Pd. 16 oz. are reported.

A. D. B.

Guidebook of the Western United States. Part C, The Santa Fe Route. By N. H. DARTON, and OTHERS. U.S. Geol. Survey, Bull. 613, 1915. Pp. 194, pls. 42, figs. 40, maps 24.

This bulletin is in all respects a mate to the preceding, organized in the same effective way. The many simple structure sections which accompany this work, and which give even the most casual reader a fair conception of the geologic structure along the route, are especially to be commended.

It is to be hoped that the demand for these guidebooks will be sufficient to warrant their revision and republication from time to time, so that they may be kept thoroughly up to date. It is suggested that in future editions a set of small maps of the individual states be added, to give the reader a more complete geographic background for the detailed route maps than is afforded by the single physical map of the United States which is included in each volume.

Bulletin 613 covers the route of the Atchison, Topeka & Santa Fe Railway from Kansas City, Missouri, to Los Angeles, California, with a side trip to the Grand Canyon of the Colorado. It is obtainable from the Superintendent of Documents, Washington, D.C., for fifty cents, postage free.

C. W. T.

"Diamond Fields of German South-West Africa." By C. W. Boise. *The Mining Magazine* (London), June, 1915, pp. 1–14, figs. 8.

These fields, which produced nearly $15,000,000 worth of diamonds in the year 1913, constitute a narrow strip along the coast in the southwestern part of the colony. The productive area is about 75 miles long, nowhere extending more than 12 miles inland. It is a barren desert, swept by the south trade winds, and has an annual rainfall not exceeding 2 inches. The coastal tract is characterized by low north-south ridges separated by stretches of sand and fine gravel, in which the diamonds are found. The productive stratum is at the surface, and averages not more than six inches in depth. The deposits are in effect *eolian placers*, in which the diamonds have been concentrated by the sifting action of the wind, which winnows out the finer and lighter material. The richest concentrations are often found in streaks parallel to the direction of the prevailing wind. The average size of the diamonds found increases toward the southern part of the field, but their original source is unknown.

C. W. T.

Coal Fields of Pierce County. By Joseph Daniels. Washington Geol. Survey, Bull. 10, 1914. Pp. 146, pls. 30, figs. 23.

The coals of this county are all in the Puget formation of Eocene age. This formation consists of sandstones, shales, and coals and attains a remarkable thickness, estimated at 15,000 feet. The beds have been

sharply folded and faulted. A heavy mantle of glacial drift covers most of the county, and details of structure are learned only from mine workings. No estimate is made of the amount of coal available.

W. B. W.

Geology and Water Resources of Tularosa Basin, New Mexico. By O. E. MEINZER and R. F. HARE. U.S. Geol. Survey, Water Supply Paper 343, 1915, pp. 317, pls. 19, figs. 51.

The Tularosa Basin is shown to be a down-faulted block between highlands of Cretaceous, older Mesozoic (?), and Carboniferous sedimentary rocks lying upon granite. The Pennsylvanian Manzano group of Red Beds here has a thickness of about 2,500 feet, and contains much gypsum. Tertiary intrusives of several types cut the older rocks. The valley bottom is covered with Quaternary deposits, comprising water-laid gravels and finer sediments several hundred feet thick, together with modern dune sands and saline deposits. There are two recent lava flows, with well-preserved cinder cones and craters.

An unusual feature of this valley is an area of 270 square miles of dunes of gypsum sand, still in motion. The gypsum is derived from deposits on the floor of a large alkali flat to windward (west) of the dune area. The gypsum of the playa in turn was derived from the bedded gypsum in the Manzano group, the solution of which has given rise to numerous sink-holes, locally so abundant as to have produced karst topography.

C. W. T.

Limestone Road Materials of Wisconsin. By W. O. HOTCHKISS and EDWARD STEIDTMAN. Wisconsin Geol. Survey, Bull. 34, 1914. Pp. 136, pls. 41, figs. 2.

The importance of thorough investigation of road-building materials is shown by the fact that this state appropriated approximately $1,250,000 for highway purposes in 1914. This report treats of limestone materials only. Part I describes various standard tests on road materials and emphasizes the importance of thorough testing. The chief limestone horizons are discussed briefly. Part II takes up by counties the limestone areas of the state. There is a brief description of limestone resources, with results of samples tested, and 40 areal geology maps of different counties. Wisconsin is said to be more abundantly supplied with road materials than any of the neighboring states.

W. B. W.

Logan and Mingo Counties. By R. V. Hennen and D. B. Reger. West Virginia Geol. Survey, 1914. Pp. 776, pls. 15, figs. 23, maps 2.

The 1914 contribution to the excellent series of county reports of this state includes two counties on the southwestern border. The general treatment is similar to that of earlier reports.

The strata exposed range from middle Pottsville to the lower members of the Conemaugh series. A large number of detailed sections of these series are given. A table of 150 coal analyses, both proximate and ultimate, is given, and under separate cover is a map showing areal and economic geology and structure geology.

W. B. W.

Biennial Report of Vermont State Geologist. By G. H. Perkins and Others. 1913–14. Pp. 448, pls. 78, figs. 41.

The greater part of this report treats of the marble industry of the state. It contains reprints of *Bulletins 521* and *589* of the United States Geological Survey which deal with commercial marbles of this area.

Separate articles by various writers give brief résumés of the geology and mineralogy in the vicinity of Hardwick, Woodbury, and Bennington. The talc deposits of the state are described by E. C. Jacobs. He believes that these deposits have resulted from the metamorphism of basic intrusions into sedimentary country schists.

W. B. W.

Biennial Report of Missouri Bureau of Geology and Mines. By H. A. Buehler. 1913–14. Pp. 62.

This is chiefly an administrative report of work completed by the survey staff during this biennial period. Statistics on mineral production in the state during 1913 and 1914 also are given.

W. B. W.

Devonian of Southwestern Ontario. By C. R. Stauffer. Geol. Survey of Canada, Geol. Series, No. 63. Pp. 341, pls. 20, map 1.

Devonian beds outcrop over the entire area of the Ontario province that projects southwest between Lakes Huron and Erie. Probably the entire system is present although the correlations of the upper and

lower members are still tentative. The beds rest unconformably on Silurian rocks ranging in age from Salina to Cobleskill or younger. The revised classification follows:

- Devonian
  - Upper
    - Port Lambton (probably Portage or Chemung)
    - Huron shale (probably Genesee)
  - Middle
    - Hamilton
      - Ipperwash limestone
      - Petrolia shale
      - Widder beds
      - Olentangy shale
    - Delaware limestone
    - Onondaga limestone
      - Onondaga limestone
      - Springvale sandstone (local facies)
  - Lower
    - Oriskany sandstone
    - Helderbergian (wanting or possibly represented in the Detroit River series)

From 2 to 10 sections are given in each of the 12 counties included in the area. The paleontology has been worked out with great care and each section is accompanied by its fauna classified by horizons. Of the species given, 350 are listed from the Hamilton beds alone and 347 from the Onondaga. Largely on faunal evidence the Springvale sandstone is considered a local facies of the Onondaga instead of belonging to the Oriskany.

There is a chapter that summarizes present knowledge of the development and migrations of the Devonian faunas in this region and a chapter of bibliography on the Devonian of the eastern continental area.

W. B. W.

Central Connecticut in the Geologic Past. By JOSEPH BARRELL. Connecticut Geol. and Nat. Hist. Survey, Bull. 23. Pp. 44, figs. 9.

This bulletin is a study of the extent to which ancient geologic structure and physiographic features may be reconstructed from data now available. Technicality has been avoided in an attempt to make the report available for general reading. To further this plan the historical geology is taken up in reverse of the usual order.

A number of wholly new structure sections are of chief interest. These sections reproduce the structure for each geologic period since late Paleozoic times. There is a departure from conventional structure sections in that clouds and the landscape of the background are added. These features may be of aid to readers untrained in geology.

Many of the generalizations on the great events of geologic history apply to a much larger area than that named in the title of the report.

W. B. W.

Peat Resources of Wisconsin. By F. W. HUELS. Wisconsin Geol. Survey, Bull. 45, 1916. Pp. 274, figs. 20, pls. 22.

As neither oil, natural gas, nor coal is found in this state, special interest attaches to its peat deposits, and has resulted in their systematic examination. Part I contains a general discussion of the origin of peat, its preparation and uses. Part II gives a description of the state's peat deposits. These are limited to the drift-covered area. The quantity of peat land is placed between two and three million acres and the amount of peat between two and three billion tons. Analyses show that for the most part the peat compares favorably in quality with peats now being used extensively in Europe.

A number of companies have engaged in peat production but all have suspended operations. It seems probable that the greater part of the peat lands will be drained and reclaimed for agricultural purposes.

W. B. W.

Soils of Mississippi. By E. N. LOWE. Mississippi Geol. Survey. Pp. 220, figs. 22.

This is a preliminary dicussion of the subject and is to be followed later by a complete report. The state is divided into 9 soil areas that correspond roughly to physiographic provinces. The soil of chief geologic interest is found in a belt of loess, that extends the length of the state, and borders the Mississippi River flood plain.

An appendix to the report contains a number of soil analyses.

W. B. W.

Hudson Bay Basins and Upper Mississippi River. U.S. Geol. Survey, Water-Supply Paper, 355, 1915.

This volume is one of a series of twelve reports of measurements of stream flow in the United States during 1913. The data cover the flow of the larger streams in Minnesota draining into Hudson Bay and those of Minnesota and Wisconsin that are tributary to the Mississippi.

W. B. W.

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THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY

With the Active Collaboration of

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THE LAWS OF ELASTICO-VISCOUS FLOW

A. A. MICHELSON
University of Chicago

When a solid is subjected to a strain beyond the "elastic limit,"[1] its behavior may be summarized as follows:

First: The application of the stress results in a rapid elastic yield which, if inertia be negligible, is practically instantaneous. If the stress be now removed, the specimen returns to its former position.[2]

Secondly: This is followed by a slower yielding whose rate, if the stress is not too great, diminishes with time and which ultimately attains a constant value which may be zero.

If the stress be now removed, the specimen returns almost instantaneously to a point short of its original position and then

[1] The term "elastic limit" is very vague and should be replaced by limits which may be characterized as follows:

a) *The first limit* is that within which the specimen returns instantly to its original zero.

Beyond this first limit, if stress be instantly removed, the specimen promptly returns to a position short of its original one, which we may designate as the "new zero."

b) *The second limit* is that beyond which the specimen does not return to its original position or to the "new zero" even after a long time.

c) *The third limit* is that value of the stress which produces rapid yielding or rupture.

[2] In many cases the time interval between application and release of stress cannot be made sufficiently short for complete, instantaneous recovery.

continues at a much slower rate and ultimately comes to rest at a point short of its original position.

If the stress is too great, the slow yield may increase until rupture occurs.[1]

The following may be considered as a provisional attempt to formulate the behavior of substances under stress by the simplest expressions which have been found to satisfy all the essential requirements.

The formulae which follow are, in fact, sufficiently general to cover every case thus far examined, including materials of widely different properties, such as lead, tin, copper, aluminum, zinc, iron, steel, quartz, glass, calcite, limestone, slate, marble, wax, pitch, gelatin, and rubber. It may, however, be expected that a more thorough investigation will require modification in the formulae which may be made to fit special cases with greater accuracy.

The type of strain selected for this investigation is the torsion of cylindrical rods, as this is the only strain in which the form remains unaltered. It is very probable that the laws governing this special type may be made to include other distortions, such as extension, compression, bending, etc.

Very decided changes may be expected from the effects of temperature and pressure,[2] but these may be taken into account by an appropriate alteration in the value of the "constants" which enter into the formulae.

[1] Rupture may occur in consequence of such slow yielding, or it may be practically instantaneous. In the former case the result is due to separation of the viscous coupling; in the latter, to the snapping of the spring.

[2] A preliminary investigation of the effect of hydrostatic pressure on elasticity and on viscosity was begun several years ago. It was hoped that this would show results in conformity with those which maintain in the body of the earth—whose enormous pressure produces an increase in both rigidity and viscosity sufficient to make the body of the earth (which at its actual temperature under ordinary conditions would certainly be in a molten state) as solid as steel. This expectation has been partially realized for a number of materials, metallic and non-metallic, the results, notwithstanding certain anomalies—traceable to the effects of previous history—showing a perceptible increase in rigidity and a very marked increase in viscosity even with the relatively small pressures obtainable in the laboratory.

The apparatus employed for the investigation consisted of a light pulley with radius of 8 cm., over which passed two cords, the ends of which carried scale pans for holding weights.

The specimen to be investigated had a diameter of 12 mm. at the ends, while the intervening portion (75 mm. long) had a diameter of 4 mm. One end was clamped to the supporting frame and the other to the pulley, which rests on a knife-edge in the axis.

The tests consisted in measuring the angular position of the pulley by a micrometer at intervals of one minute while it is under a constant torque.

LAWS OF ELASTICO-VISCOUS FLOW

The behavior of any solid under stress may be considered as the resultant of four elements: (*a*) the elastic displacement, (*b*) the elastico-viscous displacement, (*c*) the viscous displacement, (*d*) the lost motion. These will be considered in turn.

a) *The elastic displacement.*—This is characterized by being approximately proportional to the stress and independent of time.[1] A closer approximation is given by

$$S_1 = C_1 P e^{h_1 P}.^*$$

b) *The elastico-viscous displacement.*—This is manifested in a slow return when the stress is removed; and it is assumed that the same forces are brought into play during the direct motion.

[1] Doubtless there is some viscous resistance to this displacement, but it is very small compared with that of cases *b* and *c*.

* The symbols used in this discussion are:

S = displacement (twist).
P = applied torque.
F = force, stress.
C = functions of θ.
T = melting-point.
θ = temperature.
t = time.
t_0 = duration of previous strain.
$E, h, k, \alpha, P_0, a, b, m, \pi$ = constants.
e = Napierian base.

This displacement is represented by the formula

$$S_2 = A_2(1 - e^{-\alpha\sqrt{t}}),$$

where

$$A_2 = C_2 P e^{h_2 P}.$$

c) *The viscous displacement.*—Here the elastic force is absent or very small in comparison with the viscous resistance. The specimen does not return to zero even after a long time interval.[1] The viscous displacement is given by

$$S_3 = (Ft + F_0 t_0)^\rho - (F_0 t_0)^\rho,$$

in which $F = C_3 P e^{h_3}$, and $F_0 =$ the corresponding value, when P has the value P_0 during the time t_0.

For a specimen which has not been subjected to previous strain the formula reduces to

$$S_3 = (Ft)^\rho.$$

Experiment gives $\rho = \frac{1}{2}$ approximately, until the specimen is near the rupture point, when ρ approaches the value unity.

d) *The lost motion.*—If the stress be applied for a short time (even a small fraction of a second), the specimen does not return to the original zero. The difference between the original and the new zero is the lost motion L.

It seems probable that the lost motion may be considered as a function of t such as t^r, where r is very small (less than 0.02 for zinc).

If this be considered as part of the viscous term

$$S_3 = A_3 f(t),$$

then the total viscous yield may be represented by

$$S_3 = A_3[f(t) + ct^r]$$

(if the actual stress is between the limits 0 and P_0, $c = 0$).

[1] In some cases it may be made to return to the original position by heating or by alternation (alternate positive and negative diminishing stresses).

THE RETURN

If after a time t_0 the displacement has reached the value S and the stress is released, the specimen promptly returns to a displacement short of zero and continues much more slowly in the same direction.

If the elastico-viscous displacement at the time t_0 is given by

$$S_2 = A_2(1 - e^{-a\sqrt{t_0}}),$$

the corresponding return displacement at the time t, counted from the instant of release, will be

$$R = A_2 e^{-a\sqrt{t}}(1 - e^{-a\sqrt{t_0}}).$$

To account for the viscous term, assume

$$F = \epsilon S^n \dot{S}$$

whence

$$S_3 = \left[\frac{1}{\rho\epsilon}\int F dt\right]^\rho \qquad \rho = \frac{1}{m+1}.*$$

If F = constant, and F_0 = the constant value of F during the preceding stress during the time t_0,

$$S_3 = \frac{1}{\rho e}[(Ft + F_0 t_0)^\rho - (F_0 t_0)^\rho],$$

counting from the actual zero.

As shown by the formula, if the previous strain be considerable, the new strain is relatively small. This strengthening by previous strain is one of the striking features of the behavior of every substance which exhibits viscous yield.

If, in this expression, F represents the actual stress, it assumes that the viscous force is proportional to the velocity, which is true for fluids; but for "solid friction" the force is independent of the velocity.

It may be assumed in the present case of internal viscosity of solids that the actual law may be between these two extremes, e.g.,

$$P = a(\dot{S}')^K,$$

* Experiment gives $\rho = \frac{1}{2}$ (0.3–0.6), which makes $n = 1$. The usual assumption, $n = 0$, gives $\rho = 1$.

in which $K<1$. This would give P^n instead of P, or, in better agreement with experiment,

$$F'=CPe^{hP}.$$

The elastico-viscous term is readily obtained by making the viscosity coefficient a function of the time.

Thus, if the restoring force be represented by aS, and the viscous resistance by $et^m\dot{S}$,* the integration gives

$$S_2=S_0\left(1-e^{-\frac{\alpha}{r}t^r}\right),$$

where $\alpha=\dfrac{a}{\epsilon}$ and $r=-m+1$.†

To determine the effect of temperature, the behavior of zinc, glass, ebonite, pitch, and wax was studied. The results, together with the preceding, may be summarized in the following formulae:

$$S=A_1+A_2T_2+A_3T_3\ddagger$$

$$A_1=C_1Pe^{h_1P} \qquad C_1=E_0+E_1e^{K_1\theta}$$

$$A_2=C_2Pe^{h_2P} \qquad C_2=E_2e^{K_2\theta}$$

$$A_3=C_3Pe^{h_3P} \qquad C_3=F=E_3\theta(T-\theta)^{-1}$$

$$T_2=1-e^{-\alpha\sqrt{t}} \qquad h=b\theta$$

$$T_3=C+\left(t+\frac{F_0}{F}t_0\right)^\rho-\left(\frac{F_0}{F}t_0\right)^\rho \qquad \rho=\rho_0+\frac{a}{1+\left(\dfrac{\pi}{P\theta}\right)^m}$$

* The assumptions in both viscous and elastico-viscous hypotheses make the viscosity coefficient (that is, the coefficient of $\dot{S}$) zero at the beginning of the motion and infinite at $t=\alpha$, which is, of course, inadmissible. Instead of S^n and t^m we might substitute $\dfrac{B+S^n}{b+S^n}$ and $\dfrac{r+t^m}{c+t^m}$, in which $\dfrac{B}{b}$ and $\dfrac{r}{c}$ are very small; but the resulting equations are far less simple and are not appreciably more accurate in expressing the results of experiment than those here given.

† The usual assumption, $m=0$, gives $r=1$.

‡ Instead of this series coupling, the following may be substituted: The unit consists of four elements: (1), (2), and (3) are in viscous contact with (4); (1) and (2) are in elastic coupling; and, finally, (3) of this unit is connected with (1) of the next following unit by an elastic coupling. The resulting formulae, however, are not essentially different from those here given.

THE PHYLOGENY AND CLASSIFICATION OF REPTILES

S. W. WILLISTON
University of Chicago

Not many years ago it was the fashion to construct phylogenetic trees, often of wonderful design, for almost every group of animal and vegetable life. Because of the failure of so many of them, the practice has somewhat fallen into desuetude in recent years, and it is only hesitatingly that I have ventured, for the first time, to express in tabular form my own views of the phylogeny and classification of the reptiles. I do so the more readily, however, as I have no startling novelties to offer.

Phylogenetic schemes are always useful when constructed with proper discrimination and with due regard to the known and the unknown. They often furnish some residue of permanent knowledge, some real contribution to taxonomy and the doctrine of evolution; or, if not, by their failure they limit the field of legitimate speculation.

Especially has our greatly increased knowledge of the early land vertebrates, both at home and abroad, rendered it possible, I believe, to approximate more closely the real origin of many forms of vertebrate life than it was a dozen years ago. It was not long ago that we were seeking the beginning, or at least the early stages, of all reptile life in the order Rhynchocephalia. Because we found, or thought that we found, in *Sphenodon*, or *Hatteria*, as the genus was long called, the most generalized or primitive characters among living reptiles, it was not unnaturally assumed that its immediate ancestral stock was the most primitive reptilian type of the past. And when Credner discovered a quarter of a century ago, far back in the Permian rocks, another very primitive reptile, it was also assumed, too readily, that it was of the same stock. Upon that error, and it was an error, was built an elaborate edifice with the Rhynchocephalia as its cornerstone, until, as so

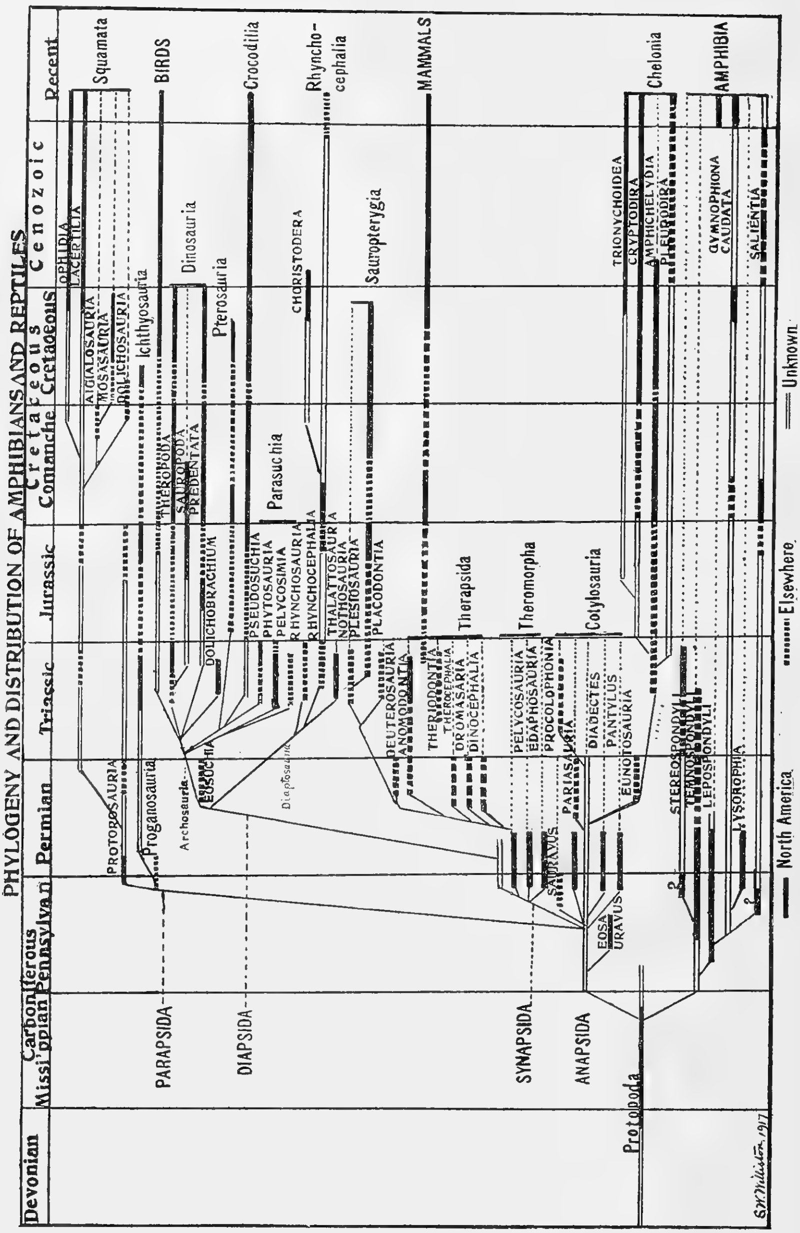

PHYLOGENY AND DISTRIBUTION OF AMPHIBIANS AND REPTILES
Devonian
Carboniferous
Missi'ppian
Pennsylvan
Permian
Triassic
Jurassic
Cretaceous
Comanche
Cretaceous
Cenozoic
Recent
Squamata
OPHIDIA
LACERTILIA
AIGIALOSAURIA
MOSASAURIA
DOLICHOSAURIA
Ichthyosauria
BIRDS
Dinosauria
THEROPODA
SAUROPODA
PREDENTATA
Pterosauria
Crocodilia
Parasuchia
Rhynchocephalia
CHORISTODERA
Sauropterygia
MAMMALS
PROTOROSAURIA
Proganosauria
Archosauria
EOSUCHIA
DOLICHOBRACHIUM
PSEUDOSUCHIA
PHYTOSAURIA
PELYCOSIMIA
RHYNCHOSAURIA
RHYNCHOCEPHALIA
THALATTOSAURIA
NOTHOSAURIA
PLESIOSAURIA
PLACODONTIA
Diaptosauria
DEUTEROSAURIA
ANOMODONTIA
THERIODONTIA
THEROCEPHALIA
DROMASARIA
DINOCEPHALIA
Therapsida
Theromorpha
PELYCOSAURIA
EDAPHOSAURIA
PROCOLOPHONIA
SAURAVUS
PARIASAURIA
Cotylosauria
DIADECTES
PANTYLUS
EUNOTOSAURIA
EOSA
URAVUS
PARAPSIDA
DIAPSIDA
SYNAPSIDA
ANAPSIDA
Protopoda
Chelonia
TRIONYCHOIDEA
CRYPTODIRA
AMPHICHELYDIA
PLEURODIRA
STEREOSPONDYLI
LEPOSPONDYLI
AMPHIBIA
GYMNOPHIONA
CAUDATA
SALIENTIA
LYSOROPHIA
North America
Elsewhere
Unknown
S.W. Williston, 1917

FIG. 1.

often in such cases, it was found that the foundation was insecure, and the edifice toppled. Everything was made to fit the uncertain base. Baur made the Proganosauria an integral part; Baur and Osborn found in the ichthyosaurs a mere wing; Broom and Osborn added a true cotylosaur; and Baur and Case built in the pelycosaurs; *Protorosaurus* and *Pleurosaurus* were mere chinks; and everybody (except Cope) united with them the lizards and snakes. I do not mention these names in any invidious spirit; they are all of men justly famous for their work in paleontology.

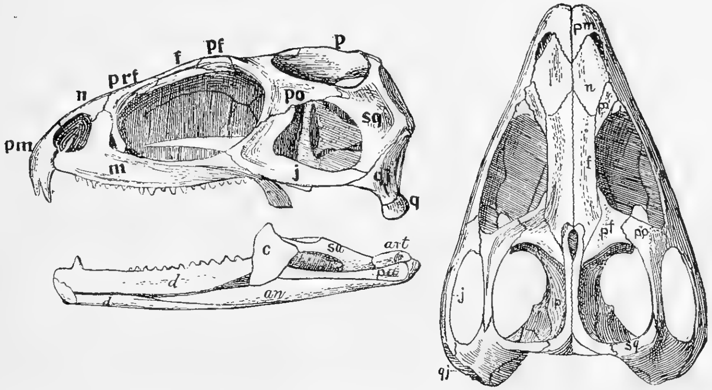


FIG. 2.—*Sphenodon*, skull from side and above. Diapsida. Recent

We all have the same proclivity, to find or to think that we find those things for which we are seeking. As Baur himself has said, they show "wie leicht man sich taüschen lassen kann, wenn man durch eine allgemeine gültige Anschauungsweise beeinflusst wird." A growing skepticism of the Rhynchocephalian affinities of *Paleohatteria* disclosed little support for the far-reaching conclusions based upon it; and, one by one, other assumptions have fallen by the wayside. A careful examination of the type specimens of *Paleohatteria* assured me that the genus was really a member of the Theromorpha. Watson holds the same opinion; and Huene has urged its relationship to the Pelycosauria.

It was Cope who, years ago, first suggested that in the temporal region of the skull the surest criteria for the classification of the Reptilia are to be found. Woodward carried the suggestion

further, and showed their availability, but it was Osborn and McGregor who first applied them definitely. They assumed too much, as we have seen, but the credit is due to Osborn, more than to anyone else, for the foundation of a true reptilian phylogeny, and to him we owe especially a better knowledge of the double-arched reptiles. He has called them the **Diapsida**, and there is no better name for them. After the elimination of the forms which we are sure do not belong with them, we are all now, I think, in accord as to their phyletic unity. It is only in details that further research (and there is much yet to be done) will be of value. The separation of the great group called the dinosaurs, first proposed by Seeley and warmly espoused of late by von Huene, into two co-ordinate divisions, the Saurischia and Ornithischia, has much to commend it. Valid arguments for the phyletic unity of the pterosaurs, crocodiles, and pseudosuchians have been offered by Huene, and their close relations with the phytosaurs and other "thecodonts" is probable. All of these have certain annectant characters, which, to me at least, are impressive. Altogether they constitute the phyletic group of the Archosauria, a term we owe to Cope.

The Diaptosauria, the other component group of the Diapsida, is much smaller than when Osborn named it; and of the few forms that are left, one, the Thalattosauria of Merriam, is discordant and uncertain. It has been offered as a connecting link between the true rhynchocephalians and the squamate reptiles; I would rather shift it bodily to the Parapsida. The Diaptosauria are the more generalized diapsids; the distinction between them and the Theromorpha is not great. The earliest assured member of the Diapsida has been carried back, I believe, no farther than late Permian, in *Youngina*, to which Broom has given the inappropriate group name of Eosuchia, inappropriate because *Eosuchus* Dollo is a true crocodile.

The origin of the Diapsida, thanks chiefly to Baur and Case, seems clear. These authors thought that the Pelycosauria were really a part of the Rhynchocephalia, and for years they were classed among them in our textbooks. It was an error, but the error has shown, definitely I think, how the Diapsida arose, by the

simple separation in reptiles with a lower temporal vacuity of the orbito-squamosal arch, leaving an upper temporal opening. The bones here are usually loosely connected, so loosely indeed in *Dimetrodon* that it is only within the past few years that we have become sure that the separation was not permanent; a permanent separation, one that would admit a knife blade even, and the deed is done. Whether or not *Ophiacodon* is a real example of this beginning, and I believe that it is, from such forms as *Mycterosaurus* the step to the diapsid type is trivial. If I am correct, and I am confident that I am, we then have the origin of the double-arched reptiles in early or middle Permian times from theromorph reptiles with a single, typically lower, temporal opening, possibly from forms not unlike *Paleohatteria*.

This group or subclass, which, with due modifications of the original concept, may properly bear the name **Synapsida** given to it by Osborn, includes scores of well-known genera of the orders Theromorpha, Therapsida, and doubtless also the Sauropterygia. It is the group that gave origin to the mammals, and has long since been extinct. In its simplest and most primitive types, together with all primitive characters of the skeleton, it has a single temporal opening bounded below by the jugal, above by the postorbital and squamosal. This opening, I believe, arose by the separation of the squamosal and jugal, and not by a definite perforation of any bone. And this opening is the sole character by which the group is ultimately distinguished from the Cotylosauria, its ancestral stock.

The evolution of the theromorph type through the dinocephalian, therocephalian, and theriodont to the mammalian seems assured by the African discoveries. In this evolution the structure of the temporal region has undergone changes of which we do not yet feel sure. The theriodont and anomodont reptiles, like the plesiosaurian, may have the temporal opening extending from the jugal to the parietal, apparently homologous with the combined openings of the diapsid forms, or, as Watson has suggested, with neither the synapsid nor diapsid; but, tracing the development as a whole, I should sooner believe that they all arose from the primitive type like that of *Dimetrodon* or *Mycterosaurus*, that is, from

a typically lower opening bounded above by the postorbito-squamosal arcade. In none of these forms does the quadratojugal enter into the opening; in some it has entirely disappeared; and the former, I believe, was the primitive condition. The opening, I believe, first appeared below and behind the orbit, at the apex of the squamosal. In the Cotylosauria the squamosal is a large bone extending far down on the side of the skull and back of the quadrate. In *Dimetrodon* and *Sphenacodon*, indeed, the quadratojugal is almost confined to the posterior side of the quadrate. Its tendency was to disappear in this type of skull, and only in some Diapsida did it become a part of the lower arch.

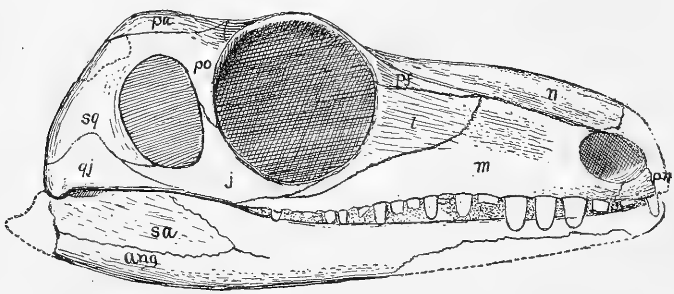


FIG. 3.—*Mycterosaurus*, skull, natural size. Synapsida, Permocarboniferous

It seems now evident that the temporal openings arose in yet another way: by the primitive separation of the postorbito-squamosal arcade from the parietal in the stegocrotaphous skull; and it seems very probable that this type of skull arose very early in geological history, as early as the lower opening, and before the separation of the upper arch in the diapsid skull. In these forms, or in most of them at least, an additional temporal bone was retained long after it was lost in other groups. And this is one of the reasons why I believe that the Ichthyosauria and the Squamata arose from a common or allied stem, direct from the Cotylosauria. For this phylum I propose the name **Parapsida.** As we have seen, Baur and others, because of the many primitive characters of the Ichthyosauria, believed that the order came from the original double-arched stem, that the lower temporal opening had been secondarily closed. Cope, in 1896, asserted that the

ichthyosaurs had an independent origin from the Cotylosauria, and so indicated in a phylogenetic diagram. Broom adopted this view in 1901. In 1904 I quoted Cope's views with approval. More recently von Huene has reached the same conclusion, finding in the Proganosauria or Mesosauria, as here accepted, either the ancestral stock or one closely allied to it. Baur, it is true, in 1887 considered the Proganosauria as the ancestral stock of the ichthyosaurs, but Baur's Proganosauria later included *Paleohatteria*, believed to be a double-arched reptile. Merriam accepted the Cotylosaurian ancestry, and Sollas very recently has voiced his approval.[1] Indeed, the opinions now seem to be unanimous and further discussion is superfluous.

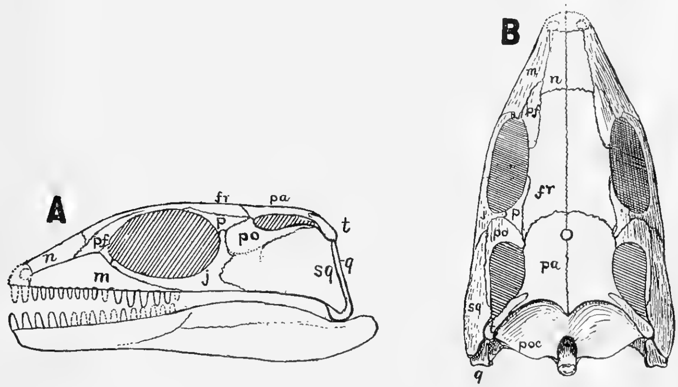


FIG. 4.—*Araeoscelis*, skull, from side (*A*), and above (*B*), natural size. Parapsida Permocarboniferous.

No order of reptiles has been the subject of more dispute than the Squamata. The apparent absence of the quadratojugal, and the presence of an additional bone in the upper temporal region, together with the freely movable quadrate, have been explained in various ways. At one time the arch articulating with the proximal end of the quadrate was considered the lower one, and the two bones the squamosal and quadratojugal. Again, the

[1] Sollas makes a rather curious error in saying that I was prepared to accept the view, with certain reservations, of the direct descent of the ichthyosaurs from the Stegocephalia. What I said was that the two bones in the temporal region of the ichthyosaurs point to a direct origin from the stegocrotaphous reptiles.

lower arch with the quadratojugal has been supposed to be lost, or replaced by a ligament, and the upper bones called by various names: supratemporal, squamosal, prosquamosal, etc. This latter view is the one now generally accepted, and, according to it, the lizards have arisen from a primitively diapsid type which, by the loss of the lower arch and the acquirement of streptostyly, has become secondarily single-arched. Twelve years ago I ventured the opinion that the two temporal bones of the squamate skull are the tabular and squamosal, the former a bone unknown or unrecognized in other reptiles since Triassic times. This view has nowhere obtained approval except by Broom. For years past von Huene, Broom, and I have repeatedly urged that the Lacertilia are a more primitive type of reptiles than the Rhynchocephalia, and, years ago, I ventured the prediction that the order would eventually be discovered in the Permian. The discovery of *Araeoscelis* in the Permocarboniferous of Texas seems to fulfil that prediction. *Araeoscelis* has a single temporal opening bounded quite as in the lizards, but with a fixed quadrate, the broad temporal region below unperforated. The cervical ribs are single-headed and attached to the centra. I am convinced that the *Araeoscelis* type of skull, by the simple emargination of the lower border of the squamosal and the consequent streptostyly, gave origin to the Lacertilia. Watson has also shown that *Pleurosaurus*, a Jurassic genus which has long been located among the Rhynchocephalia, likewise has a single, upper temporal vacuity, with a fixed quadrate, but the squamosal narrower. He believes that the genus was ancestrally related to the Squamata, though he differs from me in the interpretation of the bones of the temporal region, adopting the original Baur view of the presence of squamosal and quadratojugal. This group I have called the Protorosauria, believing that Seeley was correct in his original interpretation of *Protorosaurus*.

Whatever may be the interpretation, one thing is evident: even earlier than the origin of the upper vacuity in the Diapsida a simple upper vacuity, as in the lizards, had developed, but with the temporal region imperforate below, and this type persisted in *Pleurosaurus* to late Jurassic. If the Squamata did not originate in this way, then *Araeoscelis* and *Pleurosaurus* and probably

Protorosaurus must represent an entirely new order of reptiles, which very properly may be associated with the Ichthyosauria in the division I call the Parapsida. It might be urged that the Diapsida originated from such a type by the development of a lower vacuity after the upper one had been evolved. The arguments against this view are too many and too potent; I need not repeat them.

Admitting three chief groups of reptiles arising in late Pennsylvanian or early Permian times, we have yet another, one which by general consent is ancestral to all later amniota, the Cotylosauria, and their direct descendants the Chelonia.

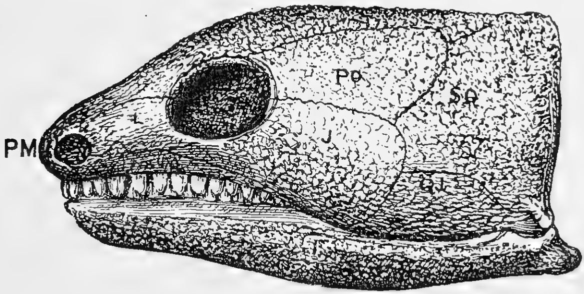


FIG. 5.—*Pantylus*, skull, from side, three-fourths natural size. Anapsida Permocarboniferous.

In this group the temporal region of the skull is wholly imperforate, and for the most part completely roofed over, a group which very properly may be called the **Anapsida**. It was Baur who first asserted that the turtles could not have originated from reptiles with a perforated temporal region. Cope derived the order directly from the Cotylosauria, through the Chelydosauria, an order based upon a misapprehension. I approved and emphasized Baur's views in 1904. Case and Hay both hold the same opinion, and only recently Watson has forcibly and convincingly presented the claims of *Eunotosaurus*, from the Permian, as a real connecting link between the two orders. And Broom and others are of the same opinion. This unanimity of opinion renders further discussion superfluous; Watson has presented the arguments.

We have, then, at least four main divisions or subclasses of the class Reptilia, all beginning in Paleozoic times, and all represented

by their direct descendants today; the birds, crocodiles, and tuatara of the Diapsida; the mammals of the Synapsida; the lizards and snakes of the Parapsida; and the turtles of the Anapsida. They suggest the following linear arrangement of the known groups, the doubtful or poorly known ones, perhaps entitled to ordinal rank, printed in italics:

Anapsida	Diapsida
Cotylosauria	Rhynchocephalia
Chelonia	*Rhynchosauria*
Synapsida	*Thalattosauria*
Theromorpha	*Choristodera*
Therapsida	Phytosauria
Sauropterygia	*Pseudosuchia*
Placodontia	Crocodilia
Parapsida	Pterosauria
Ichthyosauria	Dinosauria
Squamata	"*Eosuchia*"
Protorosauria (*Araeoscelidia, Acrosauria*)	

I am aware that other general phylogenetic schemes of the Reptilia have been proposed, especially by Boulenger and Goodrich, but long years of study of the reptiles has convinced me that, while all may have features worthy of consideration, the chief reliance must be placed upon the skull structure, especially that of the cranial and temporal regions. As von Huene and others have urged, these parts are the most conservative, and least liable to homoplastic duplication. Next to the skull, the ribs are conservative. In all the Archosauria the double-headed dorsal ribs are attached to the diapophyses. In the Diaptosauria (except Thalattosauria), the Synapsida (except the Sauropterygia), and Anapsida the rib tubercle articulates with the arch, the capitulum with the intercentral space, while in the Parapsida, so far as known, the ribs are attached more or less exclusively to the centra. Other characters originally proposed as distinctive between the Diapsida and the Synapsida in the wider sense have been proven to be invalid. We know that the primitive foot structure is nearly that of the lizards and *Sphenodon* of today, that the reduction of the phalanges in the theriodonts and turtles is purely homoplastic. The supposed relationship between the turtles and the plesiosaurs is also purely

homoplastic; nor am I aware of any constant character in the girdles, limbs, or ventral ribs. Goodrich, in a recent paper on the phylogeny of reptiles, relies greatly upon the structure of the feet, especially of the fifth metatarsal. I cannot accept his contentions, some reasons for which I have published elsewhere.

Just when the animals we call reptiles arose in geological history we do not know; certainly it was in early Pennsylvanian times, probably in Mississippian. That they arose from what we call the Amphibia, forms with temnospondylous vertebrae, is certain, though there is probably not much more reason for calling the ancestral stock Amphibia than Reptilia. I prefer to call it, provisionally, Protopoda. It was ancestral to both, and both classes have advanced since their divergence, the Amphibia some, the Reptilia much. Could we find, as some time we hope that we may, in mid-Mississippian or late Devonian times, a skeleton of one of those ancestral creatures, we should perhaps not call it by the name of any known order; it would be the old question over again of the differences between animals and plants. At present we know the Protopoda only by their footprints. As it is, we are dealing chiefly with archaic forms, even by the close of Pennsylvanian times, forms which have retained in various degrees their primitive characters while adding or losing others in different ways. Just as the most primitive mammals now living have become highly specialized in the loss of teeth, so too the amphibians, as we know them in Paleozoic times, were more or less specialized or degenerated. The only known distinctive characters between the two classes, as represented by their known skeletons in Permocarboniferous times, are found in the atlas and feet, and doubtless some time we shall find these differences bridged over. For a long time we relied upon the open palate of the Amphibia, but Watson has deprived us of that support, and now we are compelled to group the characters at length in any differential diagnosis of the two classes. However, with nearly every character in common to the Amphibians and reptiles, we are never in doubt as to which class a given form belongs if we know it well enough, for all the common characters have never been found in the same specimen, and doubtless never will be in any specimen from rocks later than the Mississippian.

OUR PRESENT KNOWLEDGE OF ISOSTASY FROM GEODETIC EVIDENCE

WILLIAM BOWIE
Chief, Division of Geodesy, United States Coast and Geodetic Survey, Washington, D.C.

For a number of years investigations have been made by the Coast and Geodetic Survey upon the subject of isostasy. The first work was done under the direction of Professor John F. Hayford in connection with a study of the deflection of the vertical and the determination of the shape and size of the earth. The later work consisted of investigations of the effect of topography and isostatic compensation upon the intensity of gravity. This work was started by Professor Hayford, and the first report on it was made to the International Geodetic Association.[1] The first comprehensive report on this work was made by Professor Hayford and the writer in Special Publication No. 10 of the Coast and Geodetic Survey which appeared in 1912.[2] The investigations of gravity and isostasy were continued under the direction of the writer, and the results have been published in two reports, one appearing in 1912 and the other in 1917.[3]

As is well known, the theory of isostasy postulates that at some depth below sea-level forces are in equilibrium and, therefore, that each column of unit cross-section extending from the depth of compensation to the surface of the earth contains the same amount of matter; or, to be more exact, it may be stated that each column

[1] *Geodetic Operations in the United States, 1906–9*, a report to the sixteenth general conference of the International Geodetic Association. Separate publication of the Coast and Geodetic Survey (not numbered), 1909.

[2] *Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Special Publication No. 10, Coast and Geodetic Survey, 1912.

[3] *Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Second Paper, Special Publication No. 12, Coast and Geodetic Survey, 1912; *Investigations of Gravity and Isostasy*, Special Publication No. 40, Coast and Geodetic Survey, 1917.

of unit cross-section which extends from the depth of compensation to the sea-level surface has the same weight.

One of the main objects of the investigations made in the Coast and Geodetic Survey is to determine to what extent isostasy is proved to exist. Other objects are to determine, if possible, the method of distribution of the compensation, horizontally and vertically, with respect to each topographic feature, and to discover, if possible, the cause or causes of the gravity anomaly which cannot be accounted for by the topography and by the isostatic compensation of the topography. By topography is meant the material above sea-level on the continents and islands and the deficiency of density in the matter between the ocean surface and the bottom of the oceans.

Professor Hayford made the following statement in his second publication on the figure of the earth and isostasy. "One may properly characterize the isostatic compensation as departing, on an average, less than one-tenth from completeness or perfection. The average elevation of the United States above sea-level being about 2,500 feet, this average departure of less than one-tenth part from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet thick, on an average."[1]

Professor Hayford based his conclusion upon the fact that the mean residual or deflection of the vertical, after the isostatic correction was applied, was 2.91 seconds of arc. After only the topographic deflection was applied, the residual was 30.37 seconds. It is seen, therefore, that the application of the effect of the isostatic compensation reduced the average residual from 30.37 to 2.91 seconds.

In making the corrections for the effect of the isostatic compensation, Professor Hayford assumed that the compensation was directly under the topographic feature and that it was distributed uniformly to the depth of compensation. This depth of compensation was an unknown quantity, to be determined from the available data. The depth derived by him is 122 km.

[1] *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, special publication (not numbered) of the Coast and Geodetic Survey.

Professor Hayford stated that the anomalies or deflections of the vertical, resulting after the application of the correction for isostatic compensation as well as for the topography, would be an indication of the extent to which the conditions postulated would not be true.

Professor Hayford should have stated that the compensation departed from perfection only 10 per cent locally, for there is no indication that there is a departure of 10 per cent from the perfect state for the whole country. Some of the anomalies were positive and others negative and these tend to balance for the whole area.

Several tests were made by Professor Hayford to show the result of other methods of vertical distribution of the isostatic compensation than the one of uniformity. If the isostatic compensation is uniformly distributed through a stratum 10 miles thick, he found the most probable depth for the bottom of this stratum to be 40 miles. If the isostatic compensation is distributed with respect to depth, according to the law postulated by Professor T. C. Chamberlin, the most probable value of the limiting depth is 193 miles. The method of distribution of the compensation by Professor Chamberlin's method is given on pages 159 and 160 of *The Figure of the Earth and Isostasy from Measurements in the United States*. This is the first report[1] on the deflection of the vertical and isostasy. In regard to the Chamberlin method, Hayford said: "It is not possible to ascertain whether this compensation is more probable than the solution G compensation, uniformly distributed from the surface to a depth of 70.67 miles, since the two sets of computed deflections agree so closely that their differences are much smaller than the accidental errors."

When the investigations of gravity and isostasy were undertaken, it was concluded that the compensation should be distributed uniformly to a depth of 113.7 km., which was the depth determined by Hayford in his first investigation of the deflection of the vertical and isostasy. The uniform distribution was adopted because it made easier the preparation of the tables with which the computation of the effect of the isostatic compensation was made. It was also believed that this method of distribution was as probable

[1] Special report (not numbered) of the Coast and Geodetic Survey, 1909.

as any other simple method of distributing the isostatic compensation. It was realized by Professor Hayford and by the writer of this paper that uniform distribution to the depth of compensation could not be true at all places; yet it was thought that the departures from normal densities in the lithosphere due to the compensation were heterogeneous and that for a large area the effect would therefore be practically that of uniform deviation from normal.

What follows in this paper is largely based upon the results of the most recent investigation of gravity and isostasy (Special Publication No. 40).

In this investigation there were used 219 stations in the United States, 42 in Canada, 73 in India, and 40 other stations, principally in Europe—374 in all.

There were certain phases of the investigation which had to be confined to stations in the United States, owing to lack of data for the other stations. These consisted of tests to show whether local or regional distribution of compensation horizontally is the more probable, and also of tests to derive the most probable value of the depth of compensation based upon uniform distribution of the compensation vertically from the surface of the ground to the depth of compensation.

Three hundred and fifty-eight stations were used for the determination of the most probable values for the constants in the gravity formula which gives the value of gravity, γ_0, at sea-level for any latitude, ϕ. This formula is

$$\gamma_0 = 978.039\ (1 + 0.005294 \sin^2 \phi - 0.000007 \sin^2 2\ \phi).$$

It is a remarkable fact that this formula agrees almost exactly with the formula derived in 1912 from only 122 stations in the United States alone. That formula was

$$\gamma_0 = 978.038\ (1 + 0.005304 \sin^2 \phi - 0.000007 \sin^2 2\ \phi).$$

This agreement between the derived formulas is a clear indication that isostasy is present to practically the same degree in other countries as it is in the United States.

The average gravity anomaly with regard to sign for stations in the United States by the adopted method of reducing for isostasy is −0.003 dyne, while the average without regard to sign for these stations is 0.020 dyne. An anomaly is the difference between the observed and computed values of gravity. The computed value has corrections applied for the elevation of station above sea-level and for the effect of the attraction of the topography of the whole world and of the opposite effect of the isostatic compensation of the topography. The topography is considered to be that material on the continents and on islands which is above sea-level and the deficiency of material in the oceans.

An anomaly of 0.020 dyne in terms of mass is here given in order that the reader may have a clear conception of the magnitude of the deviation of the gravity from normal. If we should have a disk of material directly under a gravity station and if the disk should be of normal density, 20 km. in diameter and about 600 feet thick, the attraction on a gram mass at the station would be 0.020 dyne. An anomaly of 0.001 dyne represents the attraction of a disk of material of indefinite horizontal extent and about 30 feet in thickness on a gram mass located near the center of the surface.

The anomalies by the isostatic method varied from +0.059 at Minneapolis, Minnesota, to −0.093 dyne at Seattle, Washington. There were only ten anomalies which were greater than 0.050 dyne.

When a correction was applied to the computed value of gravity for the effect of the topography, but none for the isostatic compensation, the mean anomaly with regard to sign for the stations in the United States was −0.037 dyne. The corresponding mean without regard to sign for the stations in the United States was 0.050 dyne.

The fact that the gravity anomalies were more nearly eliminated by the isostatic method of reduction than by the methods where isostatic compensation was not considered is strong evidence in favor of the former method.

We must conclude, however, that no method can be near the truth unless it has a rather general application to different sections of the country and to different classes of topography. In order

to test the methods of reductions by this theory, the stations were arranged in five groups according to the topography. The anomalies with and without regard to sign for the several classes of topography and for the two methods of reduction—one taking into account the topography and compensation, and the other only the topography—are given in Table I. To make it easier to refer to these methods the first will be called the Hayford method and the other the Bouguer method.

TABLE I

MEAN ANOMALIES

Character of Stations	Number of Stations	Mean Anomalies			
		With Regard to Sign		Without Regard to Sign	
		Hayford; Depth, 113.7 km.	Bouguer	Hayford; Depth, 113.7 km.	Bouguer
Coast stations	27	−0.009	+0.017	0.018	0.021
Stations near coast	46	− .001	+ .004	.021	.025
Stations in interior, not in mountainous regions	88	− .001	− .028	.019	.033
Stations in mountainous regions, below general level	36	− .003	− .107	.020	.108
Stations in mountainous regions, above general level	20	+ .001	− .110	.017	.111
All stations (except the two Seattle stations)	217	− .002	− .036	.019	.049
All stations	219	−0.003	−0.037	0.020	0.050

This table shows that the Hayford reduction gives about the same values without regard to sign for each class of topography while the mean anomalies with regard to sign have a very small range if we do not consider the 27 stations at the coasts. It is probable that the coast stations are affected by the presence of Cenozoic formation, the material of which is lighter than normal. This will be referred to later. We may conclude, I think, that there is practically no relation between the sign and the size of the Hayford anomalies and the character of the topography on which the stations are located.

We find entirely different conditions in regard to the Bouguer anomalies. The size of the anomaly without regard to sign at

coast stations is 0.021, practically the same as for the Hayford method of reduction. This is, of course, due to the fact that there is very little relief in the topography at the coast. The size of the Bouguer anomaly for stations in the mountainous regions above the general level is 0.111 dyne. The range is therefore 0.090 dyne.

When we consider the mean anomaly with regard to sign for the Bouguer method of reduction, we find a range for the groups from +0.017 to −0.110 dyne. This is a total range for the groups of 0.127 dyne. If we should consider the individual stations, we should find much wider ranges for the Bouguer values than for the Hayford values. The total range for the Hayford values is from +0.059 to −0.093. The total range for the individual stations for the Bouguer reduction is from +0.057 to −0.229.

The values given above are conclusive proof that the condition of isostasy exists to a rather remarkable degree, and that the theory that the topography of the earth is not compensated for by a lack of density under the continents and by an excess of density under the oceans is far from the truth.

The fact that the country as a whole is in a high state of isostatic adjustment is evident from the values given above, but there are local deviations from normal which may be due to a number of causes. They may be due to departures from the state of perfect isostasy, to an erroneous method of distributing the compensation horizontally from the station, to an erroneous method of distributing the compensation vertically with respect to depth, to erroneous values employed for the density of the topography, or to an erroneous depth of compensation; or they may be due to the presence of material heavier or lighter than normal close to the station but below sea-level. This extra or deficient density may or may not be compensated for in lower portions of the lithosphere.

There were made, during the investigation, certain tests which throw some light upon the causes of the gravity anomalies.

It has been held by some that the compensation of topography is not distributed locally under the topographic feature, but is extended horizontally to some unknown distance. It does seem improbable that the compensation should be directly under the topographic feature and not extended horizontally to a certain

extent. At the same time, it is equally improbable that the compensation should be extended horizontally and uniformly out to any definite distance from a station. It would seem to be more probable that the compensation is distributed regionally, with the greater amount of the compensation directly under the topographic feature, and that it diminishes in amount with the distance from the feature.

A test was made to show whether local distribution or regional distribution was the more probable. The distribution in each case in the regional method was uniform. The method employed was to take the average elevation of the topography within a certain distance of the station. In one case the distance was 18.8 km., in another 58.8, in a third case 166.7 km. from the station. With the average elevation within these areas, a computation was made of the effect of the compensation, which was supposed to be uniformly distributed out to the limit of the area and also uniformly distributed from the surface to the depth of compensation.

The method of distributing the compensation horizontally necessarily leads to some error, for, as a matter of fact, the compensation of each topographic feature should be distributed regionally with respect to that particular feature. But such computations would be extremely laborious and it is believed that the results would not be materially different from those which were obtained. That erroneous results might be obtained for a single station is readily perceived when we consider that the station may be on a plain or plateau, say 167 km. in radius, and that just outside of this area there are massive mountain masses. According to the theory of regional distribution of the compensation, the compensation of the mountain masses should be extended under the plains; it should therefore have an effect on the computed gravity at the station. It would tend to make the computed value of gravity at the station smaller than it would otherwise be. On the other hand, we might have a station in a mountain mass of, say, 167 km. in radius, with plains surrounding the mass. In this case all the compensation of the mountain mass would be used in the computation of the corrections to gravity. Some of the compensation should be distributed for a distance of 167 km. out into the plains.

There were 124 stations in the United States which were used in the investigation of the regional distribution of compensation. We shall speak of the three regional distributions as Zones K, M, and O,[1] since the distances given above are the outer limits of those zones. The anomalies for the local and for the three regional distributions of compensation are shown in Table II for the 124 stations.

The values in this table give no evidence whatever in favor of any one method of distribution over the others. This is probably as it should be, for most of the stations considered were in topography of low relief. When a station is on a plateau or a plain, it

TABLE II

	Anomalies			
	Local	Regional		
		Zone K	Zone M	Zone O
Mean with regard to sign..........	−0.002	−0.001	−0.001	−0.002
Mean without regard to sign.......	0.020	0.019	0.020	0.020

is evident that the method of distribution of the compensation has very little effect on the anomaly. If the topography were of exactly the same elevation throughout the zone, the local and regional distribution of compensation would give absolutely the same value. The difference in the effect would increase with the increase in the difference in elevation of the topography in different parts of the zone. While some of the stations might have larger anomalies by some one of the methods than by the others, there would be other stations for which the reverse would be true, and the mean anomaly for all the stations by each method would necessarily tend to be the same.

We may assume, as was done when considering the relation of the anomaly to the topography, that that method of distribution is most nearly the truth which has the smallest variation in anomaly for different classes of topography.

[1] This refers to the zones used in computing the effect of topography and compensation. See Special Publication No. 10.

The 124 stations under consideration were arranged in five groups, depending upon the topography. The anomalies with and without regard to sign for the local and the three regional distributions of the compensation are shown in Table III.

The mean anomaly with and without regard to sign for the several groups and for the various methods of distributing the

TABLE III

LOCAL AND REGIONAL ANOMALIES

	Local Compensation Anomalies	Regional Compensation Anomalies		
		Zone K	Zone M	Zone O
For 18 coast stations				
Mean with regard to sign..........	−0.004	−0.004	−0.004	−0.006
Mean without regard to sign.......	0.018	0.018	0.018	0.020
For 25 stations near the coast				
Mean with regard to sign..........	−0.002	−0.001	−0.001	−0.001
Mean without regard to sign.......	0.022	0.021	0.021	0.022
For 39 stations in the interior, not in mountainous regions				
Mean with regard to sign..........	+0.001	+0.002	+0.002	+0.003
Mean without regard to sign.......	0.017	0.018	0.018	0.017
For 22 stations, in mountainous regions, below the general level				
Mean with regard to sign..........	0.000	+0.001	+0.003	+0.006
Mean without regard to sign.......	0.017	0.017	0.018	0.019
For 18 stations, in mountainous regions, above the general level				
Mean with regard to sign..........	+0.003	+0.003	0.000	−0.010
Mean without regard to sign.......	0.018	0.018	0.017	0.020

compensation does not throw very much light upon the question of which method is nearer the truth, although a careful analysis of the table will, it is believed, indicate that the distribution regionally to the outer limits of Zone O, 166.7 km., is not as probable as the local distribution of compensation or the regional distribution out to the limits of Zone K, 18.8 km., or Zone M,

58.8 km. The greatest range for the mean anomalies with regard to sign is for Zone O and for mountainous regions where the stations are below and above the general level. The range here is from +0.006 to −0.010, which is 0.016 in all. This range is almost as large as the average anomaly for the United States without regard to sign. The largest range for the other methods of distribution is 0.007.

We should expect the regional and local anomalies to be approximately the same for all of the stations not in mountainous regions, but we should also expect that the local and regional anomalies would differ for the stations where the relief is great. Where the station is below the general level, the computed value of gravity is less because some of the compensation of the mountains is distributed closer to the station than it would be by the local distribution. Where the station is above the general level, the computed value of gravity is greater because some of the compensation of the local topography is distributed under the contiguous valleys.

We may conclude, I think, that the solution of the problem of local distribution of compensation of the topography is indeterminate to a certain degree; that is, that any one distribution is as probable as any other one, out to a distance of 59 km. from the station. It is possible and, in fact, probable that this uncertainty may extend to a distance somewhat greater than 59 km., but it is very probable that it does not extend to a distance of 167 km. from the station. This conclusion is based upon the geodetic evidence, as furnished by the gravity anomalies, and has no connection with geological evidence. Any decision as to whether one method or another is the more probable within the distance of about 60 km. should be left to the judgment of geologists. It is of course possible that, with more geodetic data available, geodesists may be able to throw additional light on this subject.

It should be remembered that when making the test for the most probable method of distributing the compensation horizontally the anomalies are treated as if they were due only to the method of distribution. As a matter of fact, they are probably due to a number of causes, and this fact has some effect on the results of the computation, but it is believed that its effect is small.

When the researches in isostasy and in the deflection of the vertical were started, it was assumed that the compensation of topography was complete, that it was distributed directly under the topographic feature, and that it was uniform with respect to depth. This method of distribution vertically and horizontally was continued in the computations connected with the researches in gravity and isostasy. The depth of compensation derived from investigations of the deflection of the vertical, which was considered to be of the greatest probability, was 122.2 km.[1]

As it is probably true that the gravity anomalies may be due to an erroneous depth of compensation, it was decided to compute a new value for the depth, based upon gravity observations alone. The results of these computations, with numerous tables, are given

TABLE IV

	Depth of Compensation in Kilometers						
	42.6	56.9	85.3	113.7	127.9	156.25	184.6
Mean anomaly with regard to sign, for all stations............	+0.004	+0.003	0.000	−0.003	−0.004	−0.007	−0.010

in Special Publication No. 40, and only the results need be given in this paper. In the investigations from which were determined the most probable depths from gravity determinations, there were used only the 219 stations in the United States. It was impossible to use the gravity stations outside of the United States because of lack of detailed data.

The depth 113.7 km., the one derived in the first investigation of *The Figure of the Earth and Isostasy from Measurements in the United States*, was used in making the reductions for compensation in the investigations of gravity. With the detailed information obtained from the computations it was possible to obtain the effect of the compensation for other depths. This was done by means of certain factors.

The mean anomaly with regard to sign for all the stations is shown in Table IV. The means without regard to sign for all of

[1] See *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, p. 54.

the stations used as a single group for the various depths of compensation had a range of only 0.002 dyne from 0.020 to 0.022. Owing to the small range, it is not necessary to show the means without regard to sign in the table. The anomalies in this table have not a very wide range, and therefore there is no very strong evidence to show that any one depth among the intermediate depths is much better than the others. The evidence, such as it is, favors the depth of about 85 km.

TABLE V

ANOMALIES AT DIFFERENT DEPTHS OF COMPENSATION

Character of Topography	Number of Stations	Mean Anomalies with Regard to Sign for Depth in Kilometers						
		42.6	56.9	85.3	113.7	127.9	156.2	184.6
Coast...........	27	−0.002	−0.003	−0.006	−0.007	−0.008	−0.009	−0.009
Near coast......	46	+ .002	+ .002	+ .001	+ .001	+ .001	+ .001	+ .001
Interior, not in mountainous regions.........	87	− .003	− .002	− .001	+ .001	+ .001	+ .003	+ .005
Mountainous regions, below general level...	36	.000	.000	.000	− .001	− .001	− .002	− .003
Mountainous regions, above general level...	20	+0.021	+0.016	+0.009	+0.003	+0.001	−0.003	−0.006

In order to get stronger evidence as to the most probable depth of compensation, the stations were divided into groups according to the topography, as was done in several other tests. The mean anomalies without regard to sign for the seven depths considered had a total range of 0.009 from 0.017 to 0.026. Each of these mean anomalies came in the group of stations in mountainous regions, above the general level. The maximum range for any other group of stations was 0.004 and that occurred in the mountainous regions where the stations are below the general level.

The means with regard to sign varied for the different depths and the different classes of topography. These means are shown in Table V.

It will be noticed that there is only one group for which there are very decided changes in the mean anomaly with regard to sign—

stations in mountainous regions, above the general level. The anomaly is +0.021 for a depth of 42.6 km. and it is −0.006 for a depth of 184.6 km.

Computations were made to obtain the most probable depth from all the gravity data for the 219 stations in the United States. Where all stations were used, the depth was found to be 67.1 km. It was realized that the stations on topography which was not in mountainous regions were not well adapted for the determination of a depth of compensation. Owing to the low character of the topography, the effect of the compensation was nearly the same regardless of the distance from the station to which it was extended. This is due to the fact that the attraction of an indefinitely extended disk containing a certain mass but of indefinite thickness will exert the same attractive force on a given mass regardless of how far from the disk the mass is placed. It is assumed, of course, that the attracted mass is over the center of the disk. We can see, therefore, that where the compensation is nearly the same in amount under a unit area for an indefinite distance around the station it would, although a number of kilometers in thickness, attract the pendulums at a station by the same amount regardless of the thickness of the disk or column of compensation.

The condition is different in the mountain regions for those stations which are above the general level, for there the topography near the station is comparatively limited in horizontal extent and the attraction of the compensation will depend upon the depth to which the compensation is extended. The closer to the station the greater of course will be the effect of the compensation and the larger will be the plus value of the anomaly observed, minus computed gravity. Where the compensation is extended to a great depth, the effect of the compensation is decreased, the computed value of gravity is necessarily larger, and the anomaly tends to be negative.

After consideration of all the facts, it was decided to determine the most probable value of the depth of compensation from gravity data by using only the stations in the mountainous regions below and above the general level. This was done and the depth resulting was 95 km.

It is interesting to note that, in the deflection of the vertical investigations, depths of compensation were determined for a number of groups, in addition to a depth for the whole country using all the stations as one group.[1] When we use the groups which are in mountainous regions and give the value of the depth of compensation derived from each group the same weight, it is found that the depth of compensation, as derived from deflections of the vertical data, for stations in mountainous regions only, is 97 km. It is rather remarkable that practically the same depth should be obtained from such widely different geodetic data. It is believed that the mean of these two values, or 96 km., is about the best value that is available at present from all geodetic data. As in other tests made during the investigation of gravity and isostasy, it was necessary to assume that all of the anomalies were due to the erroneous depth of compensation when the derivation of the most probable depth was made. This necessarily places some uncertainty in the depth of compensation, although it is believed that the uncertainty due to that cause is moderate in amount. It is probable that the best depth of compensation which will be derived from more geodetic data will be somewhere between 80 and 130 km. This, of course, is on the theory that the compensation is distributed uniformly from the surface or from sea-level to the depth of compensation.

The writer does not believe, as was stated earlier in this paper, that the compensation is distributed locally and uniformly to the depth of compensation. It is possible that the compensation may be distributed by some other method. It is probable that there is no method of distribution that is general, that is, applicable to each local area in the country. It seems to be most probable that the compensation varies from place to place and that the greater portion of the compensation may be near the surface in one place and lower down in another, or that it may be distributed throughout a considerable depth with varying amounts at different depths.

A computation was made, but the results of this do not appear in Special Publication No. 40, which showed the depth of the disk

[1] See *Supplementary Investigations in 1909 of the Figure of the Earth and Isostasy*, p. 58.

within which all of the compensation should be concentrated in order to have its attractive effect equal to the effect of the compensation uniformly distributed from the surface of the earth to a depth of 113.7 km. In other words, if all of the compensation were contracted to the disk at the particular depth, it would have the same effect as the uniform distribution.

If the compensation is distributed regionally to a distance of 10 km. from a station the disk within which all of the compensation is supposed to be concentrated must be placed 21.3 km. below the station. With regional compensation distributed to a distance of 20 km., 60 km., or 100 km. from the station, the depth of the disk becomes respectively 28.6 km., 41.2 km., or 45.5 km. If the compensation is started at sea-level instead of at the surface of the ground, each of the depths given above should be increased by about 1 km.

These depths are of particular significance, for they represent what may be called the effective center of the compensation on the basis of uniform distribution with respect to depth and with a depth of 113.7 km. This depth, as shown by certain tests, gives practically as good results as what may be called the most probable depth of 96 km. It is significant that there can be a variation in the depth of as much as 18 km. without materially affecting the anomalies.

It is reasonably certain that the effective depth as given above would be practically the same for all of the intermediate depths used in the computations to show which was the most probable depth. We may conclude, therefore, that the figures given above actually represent the effective center of the compensation, regardless of the method of distribution of the compensation. If, for instance, the compensation were considered to be confined to a zone about 20 km. in thickness, the center of that zone would have to be between 30 and 50 km. below sea-level. If the compensation is distributed according to the Chamberlin method,[1] the greater portion of the compensation would necessarily have to come within 100 km. of the surface, but there would be part of it at some distance below that depth.

[1] See *The Figure of the Earth and Isostasy from Measurements in the United States*, p. 160.

It would not be a very difficult matter to draw curves representing different methods of distribution of compensation which would have effective depths of the compensation equivalent to those shown above for uniform distribution. If we have the effective center of compensation about what it is for the uniform distribution, then, under any method of distribution of compensation, the greater portion of the compensation would be between the sea-level surface and about 100 km.

It may be concluded from a study of the gravity data and also of the deflection of the vertical data that there is no geodetic evidence which favors any particular method of vertical distribution of compensation. Anyone is therefore free to use a method of distribution which best serves his purpose or which may fit the particular theory he may hold in regard to the constitution of the earth's lithosphere. But, in order to secure results which are as accordant as those given in the latest report of the Survey, the effective depth of compensation must be between 30 and 50 km.

It was noticed early in the investigations of gravity and isostasy that there were apparently some relations between the gravity anomalies and the densities of the materials at the surface of the earth close to the station. This subject was treated briefly in Special Publications Nos. 10 and 12, which gave the results of the earlier investigations of gravity and isostasy. With the additional material available from other countries as well as from the United States for the most recent investigations of gravity and isostasy, these relations between the gravity anomaly and the surface density are shown to be stronger.

In the United States the stations on the dense rock which belongs to the pre-Cambrian formation have anomalies which tend strongly to be positive. This is an indication that under the station the material of this formation extends to a considerable depth where the gravity anomaly is large.

It was found that the stations on the pre-Cambrian formation in Canada did not have the tendency to be positive that was shown in the United States. This may be due to the extensive areas covered by this formation in Canada. As was stated above, the attraction of a disk of material of indefinite extent is independent

of the distance of the attractive mass from the disk; therefore, if we should have in Canada a station on an extensive area of pre-Cambrian formation where the material is of uniform thickness, and if this material were compensated for by a deficiency of material below it, then the compensation would have an effect which would practically counterbalance the effect of this denser material which is near the surface.

In India there are only eight stations on the pre-Cambrian formation, six of them having positive anomalies and two negative. But the mean with regard to sign of the anomalies is nearly zero. It may be possible that the small number of stations on this formation in India prevents the stations there from showing the same relation to the formation that we have in the United States. It is worthy of note that each of the areas of the pre-Cambrian formation in the United States on which stations are located is rather small in horizontal extent. If we should have a pre-Cambrian formation 10,000 feet thick under a station with a density of the rock 10 per cent above normal, and if the formation extended 10 km. in all directions from the station, the effect of the increased density would be to increase gravity by +0.029 dyne. If this extra material were completely compensated for and the compensation were distributed uniformly to a depth of about 114 km., the negative effect of the compensation would be −0.003 dyne. The resultant would be +0.026 dyne, which is about the size of the average pre-Cambrian anomaly in the United States.

It was found that the anomalies at stations on the Cenozoic formation had a tendency to be negative both in the United States and in India. There were only two stations in Canada on this formation and they were both negative. It is probable that the reasoning employed above in regard to the pre-Cambrian anomalies will apply to the Cenozoic anomalies. The density of the material of this formation is in general about 5–10 per cent less than normal, and the presence of this light material near the station should have a greater effect on the value of gravity than the compensation of this material, if any, which would be lower down in the lithosphere.

If the Cenozoic formation should be of great horizontal extent and of uniform thickness, the effect of material of this formation

would be offset almost entirely by the effect of the compensation if this lighter material were compensated for by an excess of material lower down in the lithosphere.

The mean anomaly with regard to sign for the Cenozoic stations in the United States was −0.007 dyne. In India it was −0.017 dyne. There were 31 stations in India on this formation and 20 had negative anomalies and 11 had positive ones. The positive anomaly in every case was comparatively small, the largest being 0.033 dyne. There were 10 of the negative anomalies larger than 0.032 dyne.

Since the publication of the results of the recent investigation of gravity and isostasy, data have become available in regard to a number of gravity stations established in the Pacific Coast states, during the summer of 1916. Of 13 stations established in southern California, each one has a negative anomaly, and the mean with regard to sign is −0.037. The largest one is −0.081. This is only slightly smaller than the anomaly of −0.093 at the Seattle station. Each of these stations in southern California is located on Cenozoic material.

There were 9 stations established during 1916 close to Seattle with 8 of them on the shores of Puget Sound. Eight of these stations were on Cenozoic formation, and 7 of these had negative anomalies. The mean anomaly with regard to sign for the stations in this vicinity which were established in 1916 is −0.033 dyne.

The writer does not wish to be understood as asserting that the Cenozoic or the pre-Cambrian material is the cause of the anomaly at the stations located on those formations. He does believe, however, that the abnormal density of the material of those two formations is the cause, or rather the principal cause, of the tendency of the gravity stations located on them to have anomalies of one sign. As was stated earlier in this paper, it is not possible from the data now at hand to tell whether or not the area covered by a Cenozoic or pre-Cambrian formation, where the sign of the anomaly agrees with the density of the surface material, is in isostatic adjustment. This is due to the fact that the compensation, if present, is so far from the station that its attractive effect is very small in comparison

with the effect of the deficiency in density in the materials close to the surface and under the station.

It seems probable that we may be able to predict with some accuracy a gravity anomaly on a Cenozoic or pre-Cambrian formation when we know the latitude and elevation of the point of observation and make a correction for the topography of the world and its compensation and apply a correction for the negative or positive attraction of the deficiency or excess of matter in the Cenozoic or pre-Cambrian formation. This, of course, is with the provision that the approximate depth and the horizontal extent of the material of these formations in the immediate vicinity of the station are known. It is also possible that where a station is located on a Cenozoic formation and has a positive anomaly the Cenozoic material is of slight thickness and is underlaid by pre-Cambrian or other extra dense material.

The stations in the United States on Paleozoic formations show a tendency to have negative anomalies. The mean anomaly with regard to sign is -0.009 dyne. The Mesozoic stations have a tendency to be positive with a mean anomaly with regard to sign of $+0.011$ dyne. There were so few stations on intrusive and effusive formations that it is believed that no definite results were obtained from a study of them. There were enough stations in the pre-Cambrian, Cenozoic, Mesozoic, and Paleozoic formations to enable one to state rather definitely that stations on any one of them have a decided tendency to have anomalies of a certain sign. There cannot, however, be any relation between the sign of the gravity anomaly and the density of the Paleozoic or the Mesozoic material, for, in general, the density of the material of those two formations is about normal.

Where the surface density is subnormal and the gravity anomaly is positive, it may be possible that there is denser material somewhat lower down in the lithosphere if the size of the anomaly is large. By large is meant somewhat above the average size of the anomaly without regard to sign. There are a number of places in the United States in which borings have disclosed the presence of crystalline rocks at varying depths below the surface where the

surface material was light in density. Dr. David White, chief geologist of the United States Geological Survey, suggested to the writer that it may be possible to predict with considerable accuracy whether or not crystalline rocks are close to the surface under a station located on surface material of light density by considering the size and sign of the anomaly.

There has been considerable confusion in regard to the opinion of Professor Hayford and the writer as to the density of material between sea-level and the depth of compensation. Some assert that we hold that the density is 2.67 for all of this material except in so far as it is modified by the compensation. As a matter of fact, neither of us has made any assumption as to the absolute density of the material between sea-level and the depth of compensation. In the investigations of isostasy it is not necessary to know the absolute density in making computations of the effect of the compensation of the topography. It is the deviations from normal densities that are given sole consideration.

A great deal of the gravity anomaly is eliminated by the application of the effect of topography and compensation, but it is certain that the remainder of the anomaly cannot be eliminated by applying the actual density of the topography in the computations. The density of 2.67 was used for all the land topography, while there are local variations in the density of material amounting to 10 per cent or more. It is, however, impossible that the true densities, if applied, could have reduced materially the average gravity anomaly. There is not enough topography to account for the gravity anomaly. It is of course probable that in many cases the anomaly would be slightly changed if a true density were used. What applies to the density of the topography will of course apply also to the density of the compensation. There is not enough compensation, however distributed, to account for most of the anomalies. As the effect of the compensation is the opposite of that of the topography, the resultant effect is smaller than the effect of the topography alone. We must conclude that no method of distributing compensation applied generally to the country or to the world will eliminate the gravity anomalies which we now have.

We must go below sea-level and below the beds of the oceans to find the cause of the anomalies. This necessarily takes the geodesist into the realm of geology, and it is there that he needs the assistance of geologists who are familiar with the geological history of the outer portions of the earth's lithosphere and of the existence of materials that deviate from normal density.

As to the process by which isostatic adjustment occurs, we must consider this largely a matter of speculation. There is no geodetic evidence on the subject. No one can say that he knows. Of many theories or opinions one is inclined to accept that which appears to be most reasonable to him.

We may summarize the contents of this paper as follows: We have sufficient geodetic data to prove that, for large areas, such as that of the United States, considered as a whole, the condition of isostasy is nearly perfect. The data also prove that the local deviations from perfect isostasy are not more than about 25 per cent on an average. If, however, we consider that the abnormally heavy or light material which is found under a number of gravity stations is compensated for by deficiencies or excesses of density lower down in the lithosphere, we may assume that the deviation locally from perfect isostasy is of the order of 10 or 15 per cent rather than of 25 per cent. The writer believes that this assumption is justified.

There is no geodetic evidence to show whether or not regional distribution out to a distance of 58.8 km. from a station is more probable than the local distribution immediately under each topographic feature. There is geodetic evidence which makes the local distribution of compensation or the distribution regionally within 58.8 km. more probable than the regional distribution out to a distance of 166.7 km. from the station. It may be possible, though the writer believes it improbable, that there is a distance between 58.8 km. and 166 km., which would give a more probable regional distribution than the distances tested.

The geodetic evidence favors about 96 km. as the depth of compensation if the compensation is assumed to be distributed uniformly between the earth's surface or sea-level and the depth of compensation. There is no geodetic evidence to show that any

one method of distribution of the compensation is more probable than other methods. It is reasonably certain that any method of distribution of compensation must have the effective depth of the compensation at a distance of from 30 to 50 km. below sea-level. By effective depth is meant such a distance below sea-level that the effect of all the compensation condensed into a thin layer at that depth would be the same as the attraction of the compensation distributed from the surface to the depth of compensation.

The absolute density of the material between the depth of compensation and the surface of the earth is not considered by the geodesist in making the corrections for the effect of compensation. It is only deviations from normal density that he considers, and it is not necessary even to know what the normal density is.

It must be concluded that the cause of the gravity anomalies is located below sea-level, and the evidence points to the probability that at least a large part of the anomaly is due to extra heavy and extra light material in the outer portions of the lithosphere which is below sea-level.

There have been found decided relations between the sign of the gravity anomalies and the geological formation. This is evidently due to the abnormally heavy and abnormally light materials in the pre-Cambrian and Cenozoic formations, respectively. There were found relations between the Paleozoic and Mesozoic formations and the sign of the gravity anomalies, but it is not evident what has caused this relationship.

There is practically no relation between the character of the topography and the sign and size of the gravity anomaly by the isostatic method of reduction. This is a very strong argument in favor of isostasy because all other methods of making gravity reductions which do not consider isostatic compensation show most decided relations between the size and sign of the anomaly and the character of the topography.

The use of gravity stations in other countries with those in the United States gave a gravity formula whose constants were practically the same as the constants of the gravity formula derived in 1912 from data at 124 stations in the United States alone. In the

1917 formula there were 358 stations used, 216 of which were in the United States.

There was not available for the foreign stations such detailed information as was available for the stations in the United States, and it was therefore not possible to utilize the foreign stations in making certain tests, but the geodetic evidence available for the foreign stations makes it practically certain that isostasy is in as nearly a perfect state in those countries as it is in the United States.

There is no geodetic evidence disclosing the process by which the isostatic adjustment takes place. This is a matter for speculation rather than proof.

The subject of isostasy is a very important one and a very broad one, and the work that has already been done is very small in comparison with what must be done in order to discover the laws of the distribution of compensation, the extent to which it is perfect, and the cause of the unexplained deflections of the vertical and the anomalies of gravity. The field is broad, and it is necessary that other scientists than geodesists should enter it. It is especially desirable that geologists and geophysicists assist in the investigation.

THE SATSOP FORMATION OF OREGON AND WASHINGTON

J HARLEN BRETZ
University of Chicago

The name "Satsop" was given by the writer[1] in 1915 to a deposit of stream gravels in the Chehalis valley of western Washington. The deposit was known then to extend throughout most of the length of this valley and to occur only in dissected terraces of stained and decayed gravel standing high above the valley floor. So far as then known, the Satsop formation rested unconformably on Eocene and Miocene marine sediments. Because of this relationship and because of its limitations as a valley filling, it was thought to be of Quaternary age.

Two field seasons have since been spent in the study of this formation in Washington and Oregon. It has been found in places along almost the entire Pacific coast line of Washington and along the Columbia River valley from the Pacific to the great lava plain east of the Cascade Range. It has been identified from the literature along the coast of Oregon. Its relations to the Coast Range and the Cascade Range are very different, and constitute the chief reason for the appearance of this paper.

The Satsop formation in the Chehalis valley.—The river gravels which constitute the Satsop formation of this valley exist along the lower 60 miles of its total length of 85 miles. The formation extends back up several tributary valleys, the type sections occurring in one of these, the Satsop valley. The maximum known thickness is 300 feet. The formation is composed of local materials and is stream-bedded with dip down the present drainage lines. Dissection has reduced the formation to a series of terraces, and decay has produced a residual loam on the surface of the highest

[1] J H. Bretz, "Pleistocene of Western Washington," *Bull. Geol. Soc. Am.*, XXVI (1915), 131.

terraces and given a dull red or orange color to the upper 50 feet of gravel.

The Satsop formation along the Pacific Coast of Washington.—The terrace gravels which constitute the Satsop formation of the Chehalis valley are traceable almost continuously in the cliffs along the lower part of this valley and in the bluffs of Grays Harbor to the sea-cliffs of the narrow coastal plain.

North of Grays Harbor the formation differs from that in the Chehalis valley only in containing much clay and sand, with fragments of driftwood. In places there are strata of peat or lignite several feet thick. The gravel in some exposures is a beach shingle and lies on wave-worn and mollusk-drilled Tertiary sandstone. The formation is horizontal for the most part, and such warping as does exist is very slight. The formation rests unconformably on Tertiary and older rocks. A few marine shells record the presence of the sea, and the interbedded peat tells of tidal marsh conditions in places during accumulation of the deposit. The thickness of the formation as shown in the cliff sections does not exceed 200 feet.

The shore line of Willapa Bay, south of Grays Harbor, is largely cliffed, and all of the cliffs are cut in the Satsop formation. Clay and sand predominate. Peaty strata record the presence of fresh- or brackish-water swamps during aggradation. Shells of marine mollusks, cross-bedding due to tidal currents, and beach shingle in the gravelly strata tell of deposition in marine water. One stratum of highly fossiliferous clay is traceable for several miles along the bluffs. Most of the shells in it are of oysters, many of the valves yet attached in pairs. The shell-bearing stratum rests on blue clay, which is full of molluskan borings but contains no shells. Above the shell bed is a peaty clay containing much driftwood. Stumps *in situ* and upright stems in this layer record succession of the oyster bed by a coastal marsh. In the gravelly strata are pebbles of granite, gneiss, schist, and quartzite, all but the quartzite considerably decayed. None of these materials occur in the drainage area of either the Chehalis or the Willapa River, while all of them are common in the Satsop formation of the Columbia valley. This gravel undoubtedly was brought over into

the Willapa Bay region by distributaries of the Columbia during the Satsop aggradation.

The Satsop formation in the Willapa Bay region is a little more than 75 feet in maximum exposed thickness, with the base below tide. The strata are horizontal or depart from that attitude only in gentle undulations.

The formation may be traced back up the Willapa valley into terraces of a decayed and red-stained river gravel which rests on eroded Eocene basalt and Miocene sandstone. The relation between the coastal and valley phases in the Willapa valley is the same as that in the Chehalis valley.

The Satsop formation along the coast of Oregon.—J. S. Diller[1] has described Quaternary sediments along the Oregon coast which belong clearly to the same formation as those along the coast of Washington. Diller did not name this formation and it has subsequently received but passing mention in the literature. Hence the name "Satsop" is here extended to cover that Quaternary formation of the Pacific Coast whose minimum limits reach from the Strait of Juan de Fuca north of Washington to the Coquille valley, within 80 miles of the Oregon-California line.

Exposures of the Satsop formation examined by Diller are as follows:

Ilwaco, Washington: 14 feet of gravel, sand, and clay, the top lying 30 feet above tide. Contains fresh shells of living species of mollusks. Unconformable on tilted shales of Oligocene age.

Tillamook Bay, Oregon: 20 feet of sandstone, capping a bluff of basalt 300 feet high.

Yaquina Bay, Oregon: Nye Beach: 40 feet of horizontally bedded gray sand overlying 20 feet of tilted Miocene shales. Sand contains logs, branches, and roots, some roots apparently *in situ*. Another section: 10 feet of yellow sand overlain by 5 feet of indurated gravel, this overlain by 6 feet of sand. Another section: 30 feet of Quaternary materials containing cones identified by F. H. Knowlton as of tideland spruce.

[1] J. S. Diller, "A Geological Reconnaissance in Northwestern Oregon," *U.S. Geol. Surv., 17th Ann. Rept.*, Part I, 1896.

Newport Point: Sand and gravel unconformable on Miocene shales. Clay contains a multitude of marine shells, identified by

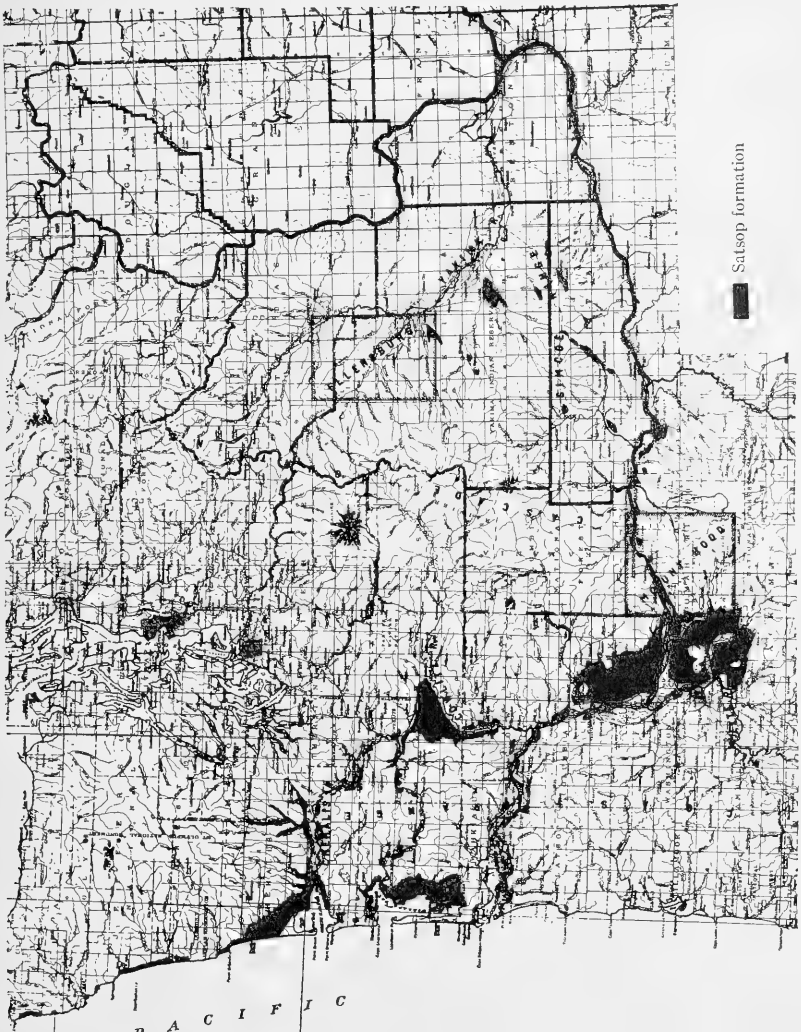


Fig. 1

Dall as belonging to six living genera. Wood and cones also present.

Coquille valley: 30 feet of sand, summit 50 feet A.T.

The Satsop formation in the Columbia valley west of the Cascade Range.—The Satsop formation in the lower Columbia valley does not differ in any essential from that in the Chehalis and Willapa valleys. It contains a surprisingly large amount of quartzite gravel. In some strata more than 50 per cent of the pebbles are of quartzite, all of which undoubtedly have come from east of the Cascade Range. Basalt, a common country rock, is also a leading constituent of the gravel. The basalt pebbles are decayed, except in the deeper portions of the deposit.

There are three large areas in the drainage of the lower Columbia where the Satsop formation covers many square miles, instead of being limited to narrow terraces. One of these areas is in the valley of the Cowlitz River, a tributary of the Columbia from the north; a second is in the valley of the Willamette River, a tributary from the south; and a third lies in a broad portion of the Columbia valley between the two areas just mentioned.

The Satsop formation in the Cowlitz valley is at least 150 feet thick. It here constitutes a broad, terraced plain and rises northward to a summit level tract about 500 feet A.T. This tract is a portion of the divide between the Cowlitz and Chehalis rivers. It bears a residual soil and with little doubt is part of the original upper surface of the formation. The pebbles in the upper 30–50 feet are softened by decay, those immediately below the soil being spaded through in excavating. At depths greater than 50 feet the pebbles are hard, but the reddish to yellowish stain penetrates as far as excavations have gone. No quartzite pebbles have been found in this part of the Satsop formation. The dissection of the tract is adjusted to a base-level recorded by a broad terrace 100 to 150 feet lower than the summit plain and about 250 feet above the present flood plain of the Cowlitz River. This terrace has been found in most of the major valleys of the region studied. From its notable development in the Cowlitz valley it is here named the Cowlitz Terrace.

Only the lower 25 miles of the Willamette valley of Oregon have been examined in the study of the Satsop formation. Most of this portion is covered by the Satsop. Numerous hills of basalt rise

through and several hundred feet above the surface of the Satsop fill. The formation is at least 600 feet thick along the Sandy River, with the base below river-level. The material is stream-bedded gravel and sand, indurated in some places to a conglomerate and sandstone. Quartzite is a common constituent for 10 miles south of the Columbia, but has not been found more than 15 miles from the master-stream. Quartzite and basalt are the most important constituents.

The Satsop formation of the lower Willamette valley is maturely dissected, the dissection adjusted to a base-level 200 feet or more above present flood plains. This level is recorded in the major valleys by a prominent terrace developed mostly in the Satsop formation but in places cut in the underlying basalt. This is the Cowlitz Terrace already described.

The uplands of this Satsop plain bear a red clay soil 10–15 feet deep. This grades down into a much-decomposed gravel. At a depth of 30 feet the pebbles are decayed only on the exterior. Below 50 feet most of the material is hard and ringing when struck with the hammer. Near the Columbia the clayey residual soil on the top of the Satsop formation contains scattered quartzite pebbles, hard, bright, polished, and apparently unaffected by the weathering which has reduced the associated basaltic pebbles to a structureless clay.

The surface of the Satsop formation in the Willamette valley lies at about 500 feet A.T. in mid-valley and rises eastward toward the Cascade Range to 1,200–1,500 feet, at these altitudes passing under the more recent lava-flows of this range. No upward slope of the Satsop surface toward the Coast Range on the western side of the Willamette valley has been found. On this side the formation terminates against hills of older basalt.

The broadened portion of the Columbia valley between the Cowlitz and the Willamette is really a continuation of the Willamette valley northward into Washington. The surface of the Satsop formation constitutes at least 200 square miles of the flat floor of this part of the valley. It is disposed in two levels, approximately 300 and 500 feet A.T., the lower of which is the Cowlitz

Terrace and the upper probably the original surface of the formation. This filling is very similar in all features noted in the preceding description to that in the Willamette valley.

Relation of the Satsop formation to the Coast Range of Oregon and Washington.—The Chehalis and Columbia rivers cross the Coast Range in capacious valleys of low gradient. In both valleys the Satsop formation has been found at closely spaced intervals from the coastal plain portion to the broad fillings east of the range. Though not continuous across the range, the character of the material of the formation, the altitudes at which it occurs, the stratigraphic relations to underlying rock and to younger gravels, and the topographic relations are such that there seems no reasonable doubt that the deposits noted in this paper are portions of the same formation.

The Cowlitz, Chehalis, Columbia, and Willamette valleys are younger than the Coast Range, and the Satsop formation is younger than the valleys in which it lies. Thus the Satsop formation was deposited after the Coast Range had been uplifted, and after its dissection was well advanced toward present maturity.

The Satsop formation along the Columbia River in the Cascade Range.—The Columbia has cut its valley across the Cascade Range down almost to sea-level. This valley is a gorge about 60 miles in length, only the western 35 miles of which have been mapped topographically. Most of the walls of the gorge are precipitous and maximum sections of 4,000 feet are available.

Numerous bluffs along the lower 12 miles of the Oregon side of the Columbia Gorge reveal a flow of gray basalt, 25–100 feet thick, in the Satsop formation. The Satsop rises northeastward in the walls of the gorge about 90 feet to the mile, bringing its base 900 feet A.T. in the salient known as Angels Rest (Fort Rock) and exposing the Columbia River lava below the Satsop. Many sections along this distance show an unconformable contact between the Satsop and the underlying basalt, and some of them show the upper 10–20 feet of this basalt to be very much decayed, far exceeding the decay of the basaltic pebbles in the lower part of the Satsop. In the section at Angels Rest the Satsop (including the intraformational lava) is 500 feet thick. A second lava-flow appears in

this section, capping the Satsop gravel and constituting the surface formation back from the edge of the Columbia Gorge. It may be traced along the cliffs to a volcanic cone known as Devils Rest, overlooking the gorge but a little back from the bluffs. Devils Rest is one of a dozen or more such cones near the gorge which have supplied the lavas overlying the Satsop formation.

The accompanying section (Fig. 2) tells the rest of the story better than would a detailed description. The intra-Satsop flow does not appear elsewhere in the range, but volcanic fragmental material is prominent in most sections of the formation. All phases of this material are present, from ash and lapilli to volcanic bombs, rudely stratified by their fall; from slightly water-rolled and poorly sorted débris to well-worn pebbles and cobbles of the gray lava, associated with equally worn pebbles of Columbia River lava and beautifully smoothed and polished pebbles of quartzite.

The Satsop deposit invariably rests on eroded Columbia River lava (a dense black basalt) and is capped by flows of gray basalt. In places the Satsop is absent and the two lava formations are in contact. The highest altitude at which the Satsop formation has been found in the Cascade Range is 3,700 feet A.T. in Benson Plateau midway across the range. Its thickness here is nearly 700 feet.

On the eastern slope of the main range the river phase of the Satsop (i.e., well-stratified gravel composed predominantly of basalt and quartzite) appears at 2,500 feet and descends eastward to 100 feet A.T. in the synclinal Hood River valley. The formation in this is

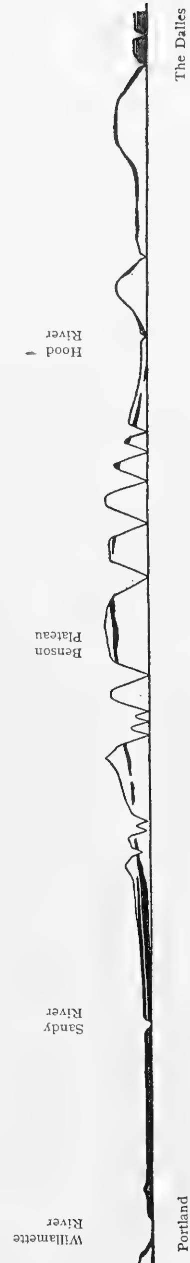


FIG. 2.—The Columbia River section of the Cascade Range. Oregon side. Looking north. Satsop formation shown in black

strikingly like that along the Sandy River, just west of the range. This is true of its composition, its structure, its degree of weathering and of cementation. It differs in having no lava-flow within the formation.

Between Hood River and The Dalles, the Columbia River has cut across two anticlinal ridges, each rising more than 2,000 feet above the stream. Each anticline is composed almost wholly of Columbia River lava. Each carries patches of a sedimentary formation composed chiefly of volcanic detritus, but containing much rounded gravel in which basalt, granite, and quartzite are present.

In the vicinity of The Dalles is a stratified deposit of volcanic agglomerate, tuff and ash, with strata of river sand and gravel, 1,000 feet thick, and capped by a flow of gray basalt. The western margin of the deposit is uptilted on the flank of the eastern anticline. Though no pebbles of quartzite or granite were found during the brief examination possible, it seems probable from stratigraphic evidence that the deposit at The Dalles is a local phase of the Satsop formation.

The Satsop formation between the Columbia and Yakima valleys.— The Simcoe Range is a prominent eastward spur of the Cascades, extending some 50 miles east of The Dalles, and separating the lower Yakima valley from the Columbia valley to the south. The range is structurally a broad anticlinal fold. Typical Satsop quartzite gravels, resting on dense black basalt and covered by gray basalt, lie in many places on the southern slope. The highest altitudes at which these gravels are known to occur in the Simcoe Range is 4,000 feet. The overlying lava does not extend far down the northern slope of the range, and the Satsop formation on this slope, unprotected by a lava cap, consists only of scattered quartzite cobbles and pebbles. All other materials in the original deposit have been destroyed by weathering. Quartzite pebbles were found as far north of the range as the southern part of the Ellensburg quadrangle. There are areas within sight of the Yakima River where these pebbles cover 50 per cent or more of the surface.

The Yakima basalt in the Ellensburg quadrangle (probably the equivalent of the Columbia River lava) is overlain by the Ellens-

burg formation, largely a sandstone of volcanic débris. Both the Yakima and Ellensburg formations have been folded into a number of east-west anticlinal ridges. Ahtanum Ridge is one of these folds in the southern part of the Ellensburg quadrangle. On this ridge the quartzite pebbles lie on the eroded edges of both the Yakima basalt and the Ellensburg sandstone. Toppenish Ridge, between the Ahtanum and Simcoe anticlines, is similarly oriented, of similar origin, and bears abundant quartzite gravel on the edges of both formations.

Relation of the Satsop formation to the Cascade Range.—It is obvious from data already presented that the outpouring of gray basalt immediately succeeded, and in part was contemporaneous with, the deposition of the Satsop formation in the Cascade Range. From the position of the Satsop formation in these mountains, it is also clear that it and the overlying lava-flows were deposited before the Cascade Range was formed.

Relation of the Satsop formation to the Methow peneplain.—Russell first advanced the hypothesis that the accordant summit levels of the Cascade Mountains in central and northern Washington record a warped and dissected peneplain. Willis and Smith[1] have named this the Methow peneplain. They have identified it on the eastern slopes of the Cascades from Lake Chelan on the north to the Yakima valley on the south. In the Ellensburg quadrangle the Methow pleneplain is thought to truncate the Ellensburg sandstone and the underlying Yakima basalt. As interpreted by Smith, these formations were gently folded before the peneplanation. Development of the peneplain brought the surface of these folds down to base-level. Renewed folding along the same axial lines is thought to have followed the truncation so that the Methow peneplain is now a warped surface lying on the tops and flanks of the anticlinal ridges.

The significant item here contributed is that the mantle of Satsop quartzite pebbles lies unconformably on the tops and flanks of at least some of these anticlinal ridges. If they constituted a stratified deposit across the eroded edges of the underlying formations, the case for planation between two epochs of folding would

[1] Bailey Willis and George Otis Smith, *U.S. Geol. Surv., Prof. Paper 19*; 1903.

be complete. However, the position of the mantle of loose pebbles is so strikingly similar to that of the stratified Satsop on the southern flank of the Simcoe Range and throughout the Cascade Range that ittle hesitation is felt in correlating the eroded surface named the "Methow peneplain" with the eroded surface beneath the Satsop formation in the Cascade Range.

But this eroded surface as exposed in the Columbia Gorge is irregular and numerous elevations in it rise several hundred feet above the base of the Satsop. This is well shown in the Willamette valley and the Hood River valley where these hills of basalt rise through the Satsop formation and the younger lavas. The surface on which the Satsop rests in the sections of the Columbia Gorge may be post-maturely eroded, but it is not a peneplain.

Further, it has been shown in this paper that the Coast Range rises above the Satsop formation in the Chehalis, Willapa, Willamette, and lower Columbia valleys and therefore was not a peneplain at the time of Satsop deposition.

The age of the Satsop formation.—Diller[1] reports that W. H. Dall found all of the species in a collection of shells from the Quaternary deposits on Yaquina Bay, Oregon, to be living forms. He also states that F. A. Lucas identified a large tooth from the same beds as that of a Pleistocene mastodon and that F. H. Knowlton identified cones from this formation as those of "*Picea stichensis* Carr.," the tideland spruce growing along this coast today.

In another paper[2] Diller has described deposits between Cape Blanco and Elk River, Oregon, about 50 miles north of the California line, which he names "Elk River beds." Dall states that the fossils collected from these beds are probably Pleistocene in age. Martin[3] has more recently examined the Cape Blanco region and reports two faunal horizons in the Elk River beds, the upper of which is very closely related to the Upper San Pedro series and "is

[1] J. S. Diller, "A Geological Reconnaissance in Northwestern Oregon," *U. S. Geol. Surv., 17th Ann. Rept.*, Part I, 1896.

[2] J. S. Diller, "The Topographic Development of the Klamath Mountains," *U.S. Geol. Surv., Bull. 196*, 1902, p. 30.

[3] Bruce Martin, "The Pliocene of Middle and Northern California," *Univ. of Cal. Publications, Bull. Dept. Geol.*, IX, No. 15 (1916).

at least Pleistocene in age" and the lower of which probably is very late Pliocene. The Elk River beds overlie the Empire beds with angular unconformity. Ralph Arnold and B. L. Clark[1] consider that the fauna of the Empire beds is "of very nearly the same age as that of the Purisima formation in the Santa Cruz Mountains of California, which is Pliocene, and not the oldest Pliocene" (Clark). The Elk River beds are apparently the same as the deposits of the Oregon coast farther north, which Diller called Quaternary.

Ralph Arnold,[2] in a description of the geology of the coast of the Olympic Peninsula of Washington, maps and names what is here called the Satsop formation as "Pleistocene gravel, sand, and clay." He notes the presence of tilted Pliocene beds (his Quinault formation), bearing a fauna similar to that of the Purisima formation of California. On these beds the Satsop formation rests with angular unconformity. B. L. Clark[3] believes that present knowledge of the Pliocene faunas of the Pacific Coast upholds Arnold's determination and that the scarcity of extinct species suggests strongly that the fauna is rather late Pliocene in age, though not the latest Pliocene.

Harold Hannibal,[4] in a paper by Ralph Arnold and himself, notes the Quaternary age of the oyster-shell bed in the Satsop formation of the Willapa Bay region.

Diller also collected fossil shells from shales 700 A.T. on the slopes of the Columbia valley 35 miles from the coast. Dall refers the shells to the Pliocene. The Satsop here is a terrace gravel down in the valley and younger than the Pliocene beds.

A clay stratum with abundant fossil leaves has been found in the Satsop formation on the western slope of the Cascade Range. Knowlton has examined collections from this bed and is of the opinion that the flora is Quaternary in age. He finds leaves of

[1] Personal communication.

[2] Ralph Arnold, "A Geological Reconnaissance of the Coast of the Olympic Peninsula, Washington," *Bull. Geol. Soc. Am.*, XVII (1906), 451.

[3] Personal communication.

[4] Arnold and Hannibal, "The Marine Tertiary Stratigraphy of the North Pacific Coast of America," *Proc. Am. Philos. Soc.*, 1913.

Quercus venustula and *Sequoia sempervirens* in the collection. Both are living species.

Age of the Cascade Mountains.—If the foregoing determinations are correct, the Cascade Range, at least in this portion, is of Quaternary age.

Acknowledgments.—During the progress of the field work on which this paper is based, nine weeks were spent with the Washington Geological Survey and four weeks with the Oregon Bureau of Mines and Geology. I wish to acknowledge indebtedness to both organizations, and in particular to Mr. Ira A. Williams, with whom I was associated during the work for the Oregon Bureau.

THE CORROSIVE ACTION OF CERTAIN BRINES IN MANITOBA[1]

R. C. WALLACE
University of Manitoba, Winnipeg, Canada

The brines geologically considered.—The Manitoban escarpment consists of a range of hills which fringes on the western side the lake system of which Cedar Lake, Red Deer Lake, Lake Winnipegosis and Lake Manitoba are the most important members, and extends southward beyond the international boundary line into North Dakota. It reaches, in the Porcupine Mountain, a maximum elevation of 2,500 feet above sea-level. At the foot of the escarpment the plain slopes gently eastward from an elevation of 900 feet to one of 700 feet. The escarpment is the eastern edge of the Cretaceous shales which extend throughout the western prairies. The shales were uplifted in early Tertiary times, and were eroded from the Red River valley back to the escarpment before the end of the Tertiary period. On this surface of erosion limestones of Paleozoic age are exposed, Ordovician, Silurian, and Devonian strata appearing successively from the edge of the pre-Cambrian shield to the escarpment; while the Dakota sandstone—the lowest member of the Cretaceous series—rests directly on the surface of the Devonian limestones. The basin of the lake system has been carved from Devonian limestones and dolomites.

At the foot of the escarpment, on the west side of the lakes, a series of salt springs emerges from middle and upper Devonian strata (the Winnipegosan dolomite and Manitoban limestone respectively).[2] These springs follow the base of the escarpment for a distance of 250 miles, but are found in greatest numbers on the west shore of Dawson Bay, at the north end of Lake

[1] Published with the permission of the Directing Geologist, Geological Survey of Canada.

[2] R. C. Wallace, "Gypsum and Brines in Manitoba," *Memoir Geol. Surv. Canada* (in press).

Winnipegosis. Around the springs are flats, absolutely devoid of vegetation, from a half-acre, as the case may be, to several hundred acres in extent. These the traveler may quite unexpectedly find in the midst of a dense forest; but the majority of the springs are to be found in close proximity to river or lake.

The brines are not confined to a single geological horizon. They appear in both the Winnipegosan dolomite and Manitoban

FIG. 1—Bowlder-strewn salt flat, Geikie's Creek, Sagemace Bay, Lake Winnepegosis

limestone, the combined thickness of which is approximately 250 feet. Owing to the comparatively level surface and the appreciable dip of the strata toward the west, the difference in elevation between the various springs is very small—not more than 50 feet. The springs may consequently be referred with greater exactness to a contour horizon than to any geological horizon.

The Dakota sandstone, which directly overlies the comparatively porous Devonian strata, is a well-known water-bearing

horizon in the middle northwestern states and in the western provinces. It is capped by impervious shales, and the water, which circulates under considerable hydrostatic pressure, apparently penetrates laterally into Devonian strata, leaches sodium chloride from certain horizons in which the salt has been precipitated with the limestone, and reaches the surface where the covering of drift is thin or absent. On an average approximately 430 gallons of brine reach the surface per minute during the dry season; and the salt, if evaporated, would cover the main salt area (200 miles by 30 miles) with a coating 2 feet thick in 10,000 years.

TABLE I

	Brine*	Sea-Water†		Brine*	Sea-Water†
K	1.37	1.11	HCO_3	0.20	....
Na	34.99	30.59	Cl	55.95	55.29
Ca	2.02	1.20	Br	0.04	0.19
Mg	0.55	3.73	I	Nil	....
Fe	....	....	Si	0.03	....
Al	0.01	....	Percentage salinity	7.29	3.30 to 3.74
SO_4	4.88	7.69			
CO_3	Nil	0.21			

* From Salt Creek, Salt Point Peninsula, Lake Winnipegosis. Professor M. A. Parker, analyst.

† Mean of 77 analyses by W. Dittmar.

Composition of the brines.—Numerous analyses have been made of the brines. The composition is remarkably uniform, differences occurring only when the brines pass through a considerable depth of glacial drift before reaching the surface. In this case the percentage of Ca and SO_4 ions is considerably greater than normal. Table I gives the analyses of a typical brine, Dittmar's average of 77 analyses of sea-water being given for comparison.

The analyses are given in percentages of total solids. The percentage of salinity in the analysis quoted is somewhat greater than normal, but the percentage values for the constituents vary only slightly from the figures quoted. While on the whole the brine is very similar to sea-water, it is a distinctly purer solution of sodium chloride. The relative percentages of Ca and Mg ions differ in a sense, which may be accounted for by the abstraction of Ca ions by marine organisms. The apparent differences in the carbonate

values are due to the fact that in the statement of the analysis of sea-water the total carbonate is reckoned as normal carbonate. The concentration of the brine is, however, notably higher than that of sea-water.

Action on the bowlders.—The glacial drift was to a large extent derived from the pre-Cambrian areas in the north. The bowlders which cover the bare flats where the salt springs are found are mainly gneissose or granitic, though occasionally dark-green epidiorites or Paleozoic limestones are seen. Chemical solution has taken place on an extensive scale, many bowlders having been reduced on every side by at least a foot. This is very clearly seen in the salt creeks in which the water is carried from the springs to the lake, the bowlders standing on a much-eroded base, like the rocks of a great sand desert. On the flats the bowlders are pitted into very fantastic forms, the ferromagnesian minerals having suffered to the greatest extent. Not even quartz nor garnet has escaped the action of the solvent. Gneissose structures are accentuated by differential weathering, garnetiferous bands standing out in special relief. As the corrosive power of the brine is apparently much more intense than that of sea-water, it is of interest to inquire into the processes involved in the disintegration of the rock.

Chemical processes.—Regarded as a chemical agent, the brine may be considered to be a weak solution of sodium chloride. A considerable amount of experimental work has been done on the action of solutions of sodium chloride on minerals, but the evidence is somewhat conflicting.[1] Joly has, however, proved that sodium chloride, in the presence of the atmosphere, is a more active disintegrating agent than pure water. Daubree's experiments were conducted under somewhat different conditions. In the case of the brines physical conditions have been favorable. Normally the salt crystallized in thin crusts at the base of the bowlders. The salt is somewhat deliquescent, and gradually extends upward over the side of the bowlder, till a thin coating of brine, somewhat diluted during the process, covers the whole bowlder. The conditions are thus most favorable for chemical activity in presence of the atmos-

[1] Daubree, *Synthetische Studien zur Experimentalgeologie*, 1880, 205; Thoulet, *Compt. Rendu*, CX, (1890), 652; Joly, *Proc. Roy. Irish Acad.*, XXIV (1902).

phere; and the writer believes that it is primarily as an agent for distributing the liquid in a thin film over the bowlder, and only secondarily as a direct chemical agent, that the dissolved material in the brine acts in the process of disintegrating the bowlder. It has been proved conclusively that water is itself an agent of considerable chemical power and that it acts most vigorously as a

FIG. 2.—Corroded bowlder, salt flat, Pelican Bay, Lake Winnipegosis

corrosive agent when in intimate contact with the atmosphere, as, for instance, at a water surface.

The actual process of disintegration is necessarily different for different minerals. The ferromagnesians, more particularly the amphiboles and pyroxenes, have suffered to a greater extent than the feldspars. The alkaline earths are somewhat readily attacked and dissolved as carbonates or chlorides, and silica with alumina, mixed or combined, is left in colloidal form. The percentage of soluble material in the case of the feldspars is correspondingly smaller. To some extent, with the metasilicates at least, the

process is one of hydrolysis; and while it may be effected by water alone, it is doubtless hastened by the carbon dioxide of the atmosphere. The gels which are formed during the process of decomposition are irreversible—that is, they cannot, by the action of electrolytes, pass over into sols and be in this way removed from the sphere of action. They exercise, however, a selective absorption, alkalies being removed from the brine while the acid radicals remain in solution. With potassium salts in particular this property of the colloids of the soils is of importance in retaining the valuable ingredients of fertilizers. This selective absorption tends, therefore, to hydrolyze the chloride, and to render the solution more acid. The free acid reacts on the partially decomposed minerals, causing further disintegration. Quartz is not affected thereby, but the corrosion of quartz is in all probability due to the action of alkaline carbonates.

In short, then, the principal fact in the disintegration is the intimate contact of the liquid (in a very thin film) with the atmosphere and the rock. The initial stages of the disintegration are caused by the action of water in contact with air rather than by that of salts in the water. Colloidal precipitation, which takes place when decomposition of the silicate begins, leads to selective absorption and consequent acidification of the solution, giving rise in turn to further, and probably more intense, disintegration. The process is continuous, gel being continuously precipitated, and further selective absorption taking place. The gel, being irreversible, is not taken up as an emulsion, and can consequently be removed only mechanically.

Comparison with the action of sea-water.—On comparing the action of sea-water on bowlders of similar composition to those attacked by the brines, one finds an undoubtedly real difference in the degree of corrosion. It is, however, a difference in degree, not in process. The evidences of chemical erosion caused by the sea-water are to a large extent removed by mechanical attrition caused by the impact of the waves on the bowlders, and the consequent rolling of the bowlders on the beach. Even in large bowlders, however, where rolling is reduced to a minimum, the evidence of chemical disintegration is small indeed in comparison with that of

the bowlders from the salt flats. The relatively small difference in concentration of sodium chloride is not sufficient to account for the difference in chemical activity in the two cases.

Bowlders between high and low watermark are situated similarly to those on the salt flats in one particular—they are in intimate contact with the solution and with the atmosphere. They are

FIG. 3.—Corroded bowlder, salt flat, Pelican Bay, Lake Winnipegosis

differently placed, however, in that they are alternately water-covered and dry to the base. Evaporation does not proceed so far that sodium chloride is precipitated, and films of liquid are not fed over the surface of the bowlder from the base. The initial disintegration of the bowlder is consequently less readily effected, and the acidification of the solution through absorption is to a similar extent retarded.

While to different physical conditions may be attributed the difference in degree of corrosion of beach bowlders and bowlders

of similar type in salt flats, the fact of chemical erosion by sea-water is emphasized by the study of the action of this essentially similar brine. The chemical action of sea-water on igneous rocks between high and low watermark must be much more considerable than is generally believed. The disintegration attributed to mechanical attrition is undoubtedly, in part, at least, chemical. Sea-water under great pressure is apparently a solvent for the volcanic débris which reaches the bottom of the deeper ocean; but the solvent power is intensified by contact with the atmosphere, even at ordinary pressures. Conditions are most suitable when the three phases—solid, liquid, and gas—remain in intimate contact for considerable periods of time. Such is the case where shallow pools of water are imprisoned in the hollows of the rock surfaces when the tide recedes; in these cases evidences of corrosion are very clear.

It would be futile to attempt to compare in intensity the action of sea-water on beach bowlders and that of rain-water impregnated with humus acids from the soil. Data are not available in the field. It must suffice, at this stage, to rank sea-water and acidified rain-water side by side as two potent agents from the chemical, as from the mechanical, standpoint, in the disintegration of rocks.

NOTES ON THE 1916 ERUPTION OF MAUNA LOA

HARRY O. WOOD
Hawaiian Volcano Observatory

III

The writer spent the two days and night of May 30 and 31, 1916, in making a hurried reconnaissance of the Kahuku branches of the recent flow, and of the region near its source, where action was still going on, though the eruption already had greatly diminished. There had been no forward movement of the flows at their fronts later than May 27 or May 28. A preliminary account of this work was published at once in the *Weekly Bulletin* of the Hawaiian Volcano Observatory.[1] However, difficult foot traveling was encountered, and somewhat adverse weather conditions, which prevented thorough and accurate work; and the presence of fog and fumes led to erroneous estimates of distances and heights; also, our guide applied place-names incorrectly and his errors naturally found place in the early report. Further, observations of much interest, but not pertinent to the present subject, were included in that account. Hence an abridged and corrected statement relating to the 1916 action finds appropriate place here. Much that was only glimpsed on this hurried trip was fully confirmed by the later study. Whence certain observations thus confirmed it is convenient to mention here.

ITINERARY

The writer and one companion left the observatory in the early evening of May 29 and motored to the village of Waiohinu, where the night was spent. Early the next morning we motored to a gate of the Kahuku ranch about a mile west of the ranch buildings. Here we were joined by the guide, and the party set out on horseback at 8:00 A.M., going up the south slope of the mountain between

[1] Vol. IV, 6, pp. 51–57.

the flows of 1868 and 1887. At 10:30 A.M. we reached the southernmost "toe" of the front of the Kahuku branch of the 1916 flow. Here we turned off to the right to pass around this flow and up on the east and north of it. We followed an upland trail toward Kapapala until we came into a *Kipuka*, a long, narrow strip of forest land extending up the mountain between two barren streams of *a–a*, known by the name Kipuka Akala. At the lower end of this we left our horses. We reached it shortly before noon, and at noon we set out on foot up the mountain, taking a northwest course toward the general source of the new flow, north of the conspicuous cluster of cinder cones marked Puu o Keokeo on the government map. (There is dispute as to whether this name is correctly applied to this group of cones, but there is no doubt that the members of the group so mapped were those identified.)

As we planned to spend the night near the source we were necessarily laden with food, water, photographic equipment, etc., and blankets or extra clothing—a moderate load for each man. For about an hour we made our way upward alongside the strip of forest, but walking in the open chiefly over old *a–a*. At about 1:00 P.M. we came out onto a barren, complex network of *a–a* flows of varying direction and age—much of this apparently of 1907 date—and over this very difficult surface we clambered until a little after 5:00 P.M. We then had reached an old cinder cone situated between two and three miles from Puu o Keokeo in a direction a trifle east of north. This cone was about a quarter of a mile east from the rift-line source of the 1916 flow described below. We had not reached the upper limit of this source, which had been our goal, but it became impracticable to go on farther. Here we stationed ourselves in the lee of this old cinder cone and passed the night, practically all of which the writer devoted to observation of the action and conditions along the visible length of the rift source.

At 4:50 A.M. on May 31 we began the descent. At 9:40 A.M. the horses were reached, and at 10:15 A.M. we started on our way to Puu o Keokeo, going around the southern end of the Kahuku branches of the flow and up on the western side of them. By noon we reached a flat clearing, where we dropped our camp equipment

and immediately proceeded upward on horseback to a point very near to Puu o Keokeo, on a low ridge of ancient pahoehoe which extends a short distance eastward from the conspicuous cluster of cinder cones. In clear weather this slight eminence affords an expansive view to northward, and much wider views can be obtained from the summits of the cones near by. On this occasion we obtained only partial views through driving fog and clouds, and in brief clear spells between small local showers. We reached this point of outlook at 2:20 P.M. It was impracticable to keep horses here overnight, and unnecessarily uncomfortable to remain ourselves without camp equipment in such unsettled weather, especially as our hasty reconnaissance was completed, so we began our descent at 2:35 P.M., and returned on horseback to Waiohinu, which we reached at 8:30 P.M. We returned to the observatory the next day.

Thus we passed completely around the Kahuku branches of the new flow, except for their breadth near the source. In this way, especially on the foot journey, and also from the ridge near Puu o Keokeo, a good general survey was obtained of conditions along these and near their source; and in limited localities, particularly those encountered on foot along the eastern side of them, many matters of detail were observed. Conditions of the traveling, distance, and weather prevented examination of the upper limits of the source, of the action and conditions on the sides toward Kona, and the making of photographic records.

GEOGRAPHICAL NOTES

The closely grouped cluster of old cinder cones, named Puu o Keokeo on the government map, of which the highest point is 6,870 feet above sea-level, forms a low but conspicuous landmark on the south-southwest flank of Mauna Loa. Extending east-southeastward from this for a half-mile or less is a low ridge of ancient pahoehoe rising from 30 to 50 feet above the surrounding country.

A long narrow belt marked and characterized by many cinder cones (double semicones built by spatter outfall on both sides of open rift cracks in parallel linear arrangements) leads upward in a

practically straight line from a point a little west of this conspicuous group to the summit plateau of Mauna Loa (see the photographs, Plate VI, *a* and *b*). North of this lava ridge and east of the belt of cinder cones (and to a less extent west of it also) is a comparatively flat area. For a considerable distance to the northward toward the summit, the surface of this stands at a lower altitude than the summit of Puu o Keokeo, and its eastward extension from the belt of cones, though variable, has a width of from two to three miles. This makes a very conspicuous upland flat of very slight grade on a broad dome surface which is itself of very gentle slope. South of Puu o Keokeo the usual slope of the mountain is resumed. At the southeast and east this broad, irregular flat passes imperceptibly into the irregular, broken slope of the dome. Several miles to the north of Puu o Keokeo the flat passes rather quickly, though the region of transition is indefinite, into the somewhat steeper slopes which rise to the summit plateau. Viewed from the ridge south of this flat, Mauna Loa appears as a distinct mountain until the genetic significance of the long belt of cones is understood (see the photographs, Plate VI, *a* and *b*).

This belt of cones marks an unmistakable major rift zone, which joins at the summit with that leading down the northeast flank of the mountain—a great crust fracture, as a whole slightly curved and convex to the northwest, through the whole dome of Loa. This stretches northward across the flat and bounds on the west that part of it seen on this reconnaissance.

SOURCES OF ERUPTION

As was anticipated, the sources of the eruption of 1916 were found to lie in this major rift zone. Both the sources of earliest outbreak, high on the dome, and the sources of flow lie in it. Both were seen to constitute segments of the rift zone, and to be themselves rift traces in this zone.

THE SOURCE OF EARLIEST OUTBREAK

A long fissure marked by constant emanation of steam (or fumes) was seen leading from near the summit plateau of Mauna Loa down the south-southwest side of the upper slopes of the dome

nearly to the region where this grades into the great flat—a distance of several miles (see the photographs, Plate VI, *a* and *b*). For the most part the steam was clinging to the surface along the line of fissure; but at one point (and possibly a second) it was rising definitely in small volume. Unquestionably this eruption marks a minor rejuvenation in 1916 of the action of rifting through Loa, and in this upper segment were the orifices, large and small, from which came the outrush of fumes in the morning of May 19. The place, or places, where steam appeared to be rising definitely was well up the slope beyond its transition into the flat. The line of fissuring marked by steam emanation possibly is interrupted, and perhaps is offset *en echelon*. This could not be determined positively when seen from so considerable a distance. This fissure leads down in line with the primary system of double semicones which stretch across the flat along the rift zone from near Puu o Keokeo. This line of new steam emanation was seen definitely at all times when the upper slopes were in the field of vision.

THE SOURCE OF FLOW

The source of flow was found to be a freshly opened rift crack or, more precisely, a long, narrow system of closely spaced parallel cracks. This ran in a direction slightly oblique to that of the broad rift zone, but confined well within the limits of it, for some three miles or more, tending very slightly to the west of north from Puu o Keokeo across the flat toward the summit. Its upper limit was not reached on this reconnaissance. Out of these fresh cracks gushed the molten lava which streamed away toward lands in Kona, and toward Kahuku—the streams dividing at the northern base of the group of old cinder cones at Puu o Keokeo. Only the Kahuku branches were seen on this reconnaissance.

OBSERVATIONS NEAR THE SOURCE

Our bivouac for the night of May 30–31 was in the lee of an old triple-peaked, double semicone in the south re-entrant, where its parts straddle an ancient cinder-choked fissure. This cone was elongated in the north-south course of this fissure. It had been the source of an ancient eruption of pahoehoe. This station was

between two and three miles from Puu o Keokeo in a direction a trifle east of north. Just west from here, about a quarter of a mile away, was one of the two larger cinder cones of 1916. This was a double semicone built on either side of the new rift crack. Both north and south of this new cone were several other new cones. A flow of *a–a*, undoubtedly of the date of 1907, separated us from the line of vent of the latest activity.

Though greatly diminished, there was still vigorous action at many points along this line. At first the most active point was a cinder cone near the northeastern base of Puu o Keokeo, between two and three miles almost due south of us (see the photograph, Plate VI, *d*). Though this was down the wind, which was gentle, however, explosive coughing sounds could be heard at frequent irregular intervals; and occasionally red-hot masses were thrown up into our field of vision. This action continued throughout the evening and the early part of the night. During this interval the glow above this vent was considerable, though less than that ordinarily seen above Halemaumau as viewed from the observatory at about the same distance (yet, through the disturbed air, it appeared to be comparable with this). However, at about 8:45 P.M., May 30, a short, sharp earthquake occurred, plainly felt by all three of us sitting or reclining on the cinders in the fissure re-entrant of the old cone. (This shock was felt sharply at Waiohinu and at Kapapala. At Hilea it was felt as the strongest shock of the entire series connected with this eruption.) Within less than a minute, but more than thirty seconds, after this shock there occurred a spasm of greatly increased action at the vent mentioned, with the jetting of lumps of incandescent lava high in the air, and a great increase in the glow. However, the action again quickly subsided to normal. Afterward the action at this vent declined, at first slowly, but toward 1:00 A.M., May 31, more rapidly. By 3:00 A.M. the situation of this vent could barely be made out. When seen again in midafternoon, on May 31, from near Puu o Keokeo, only a smoking cone appeared. There was no revival of activity afterward, so doubtless we witnessed the dying of action at this vent.

In the late afternoon of May 30 a glowing cone was seen, showing an oven-like orifice, situated at a distance of two hundred

to three hundred yards to the northeast of the vent just described. But after night fell the glow above this was negligible.

Between the new cone directly west of our bivouac and the place of greatest activity just described fumes were rising steadily from numerous larger and smaller vents and cones. After darkness came on three of these fuming places exhibited glow. From our viewpoint this glow came and went intermittently, but this appeared to be due to drifting fog and fumes alternately concealing and disclosing the illuminated fume columns.

The larger new cone just west of our bivouac showed steady, vigorous glow on the fumes at both its north and south extremities. These were separated by a dark interval of about 200 feet. No incandescent matter was thrown from this cone into our field of vision.

To the northwest, at a distance of about a third of a mile—hence probably more than $2\frac{1}{2}$ miles from Puu o Keokeo in a direction a little west of north—was a cone which in some respects exhibited the greatest activity of any of the vents, though it was not conspicuous for glow. Indeed, it was remarkable for the comparatively slight amount of illuminated fumes which appeared to spread from it. By daylight this cone was not seen clearly, owing to drifting fog and fumes; but at night it became plainly visible. It was still building. There were numerous incandescent gashes and glow-spots on its sides which remained without substantial change throughout the hours of the night. These were interpreted as true gashes and orifices in the shell of the cone, throngh which shone out the incandescent core. Almost incessantly red-hot masses were thrown out of this cone into the air. Most of these barely cleared the summit to tumble and roll down the sides of the cone. The relative motion of these between and among the practically permanent orifices created the illusion of a steady fountain-play of fiery particles high above the summit of the cone, rising and falling like droplets at the top of a jet of water. It required prolonged observation to correct this impression. At intervals of from twenty seconds to three to five minutes, larger masses were projected into the air high above the apex of the cone. These usually would describe free parabolic curves to fall, apparently, beyond the base of the cone. In most of these cases no rolling was seen. At

the time exaggerated estimates were made of the distance of this cone, and therefore of its height, the height of projection, and the sizes of the projected masses. Drifting fog and fumes gave a greatly lengthened perspective effect. Afterward the cone was visited and found to be distant about one-third of a mile from this bivouac, and to be about 30 feet in height. Whence the height of projection of the molten lumps, at highest, was about 45 feet above the apex of the cone, or 75 feet above its base. No large cinder lumps were found about it. Though the cone was situated across the wind from us, a steady, gentle drift of air, loud, staccato, explosive booms could be heard occasionally accompanying the projection of the larger masses. This cone was the most spectacular remaining center of activity of any which came within our range of vision. On the southwest side of it there was an intermittent illumination of the thin fumes, of a sort which suggested outflow of lava coursing away in the southwest direction. However, the later visit determined that this was a spatter cone higher up the rift than the head of flow, and that any flowing from it was very local and confined within a very small area.

Farther north was seen a glowing orifice like an oven which probably was a gash in a quiet cone. Still a little farther up, rising fumes were seen, but these showed no illumination at night. After darkness fell, nine places altogether were distinguished where rising fumes were illuminated. All of these but one were aligned along the rift crack northward from the chief vent at the northeast base of Puu o Keokeo. The other was the oven, situated a little way to the northeast of this chief vent.

Small quantities of new basaltic pumice, yellow in color, usually in elongate stringers, were found in close proximity to the rift source near its head at the east.

THE KAHUKU BRANCHES

The Kahuku branches of the 1916 flow run in southeast and south-southeast directions from points along the rift source beginning at the base of Puu o Keokeo and extending northward for more than a mile. On our foot journey, on May 30, from 3:00 P.M. on we kept encountering little fuming areas lying to the south of

our route, which indicated the courses of tongues of the new flow. We approached these quite closely as we neared the rift. The trunk of this flow departs from the source at Puu o Keokeo in an east-southeastwardly direction, passing along and around the end of the ridge of ancient pahoehoe that juts out from the cluster of cones; there it swerves to the south-southeastward and spreads down the mountain.

Near the source the lava was pahoehoe in typical surfaces and in broken crusts and fragments. Except near the source the lava in these branches was *a–a* wherever they were approached closely enough for this to be determined. At points on the east these tongues were thin, from 5 to 10 or 20 feet deep; but at the south and along the west the lava blocks were piled irregularly from 20 to 40 feet deep, or high, and were still hot and fuming on May 31.

In passing from the southernmost point to the eastward and northward many thin, narrow tongues (from 5 to 8 or 10 feet in depth, and from 50 to 200 yards in width) were encountered radiating to the southeast and east. These departed from the main stream at higher and higher points. Wherever junctions were seen the departures of these minor branches appeared capricious; that is, no evidences of local damming or pooling were seen. Though thinner and much less massive than the more western streams, these were still fuming, and in varying degrees the air above them was in a state of shimmer from heat. However, the emanation of the fumes furnished a more reliable indication of their courses than the heat-disturbed air above them. (Probably tongues, or "toes," project from the main streams on the western side, as others report who viewed them before they ceased flowing; we found no opportunity to follow the margin closely and did not note any conspicuous projections.)

Any adequate cartographic delineation of the complex out-branching of this Kahuku part of the 1916 flow can be accomplished only by actual topographic survey. (A reconnaissance survey was made in June, 1916, by a party under the Hawaii Territory Survey. An adapted, and in some details corrected, modification of this follows, as Fig. 1. A general conception of a long, narrow,

branching flow (about $5\frac{1}{2}$ miles long) to the southeast and south-southeast, with many minor spreading tongues, is all that could be developed as a result of this reconnaissance.

When we were in the neighborhood of the new lava, smells of subliming sulphur, sulphur acids, charcoal, and cinders were very noticeable. There were also smoke smells from burning vegetation.

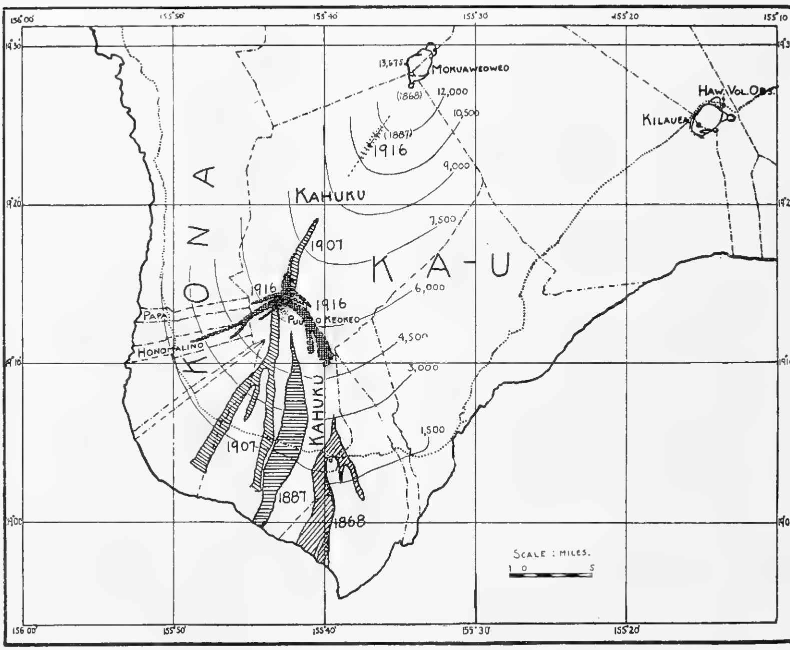


FIG. 1.—A *diagrammatic* map of the 1916 flow and the neighboring region, adapted from a reconnaissance survey by the Hawaii Territory Survey, June, 1916, with corrections and modifications suggested by field work and reports. This plate also shows a *diagrammatic* correction of the course of the 1907 flow near Puu o Keokeo.

IV

The thorough exploration of the region of the source of flow made in company with Dr. A. L. Day in late June and early July served to correct or confirm the findings of the hurried reconnaissance made in the last of May, and to enlarge their scope materially. Also many photographs were made, affording a fairly complete pictorial record of the results of the action at the source. However,

our efforts on this occasion were devoted in large measure to observation of details and to the examination of evidence bearing on the physical-chemical conditions and the mechanisms of flowing in the lava streams near their head. The ideas considered in this connection are best left for future discussion by the writer's companion on this expedition. Here it will suffice to say that much was seen tending to confirm, and some things tending to modify, the writer's conception of the mode of flow of *a–a*, as exemplified by the action observed at the front of the Honomalino branch, described above. Consequently, the space here devoted to this more thorough work is small in proportion to its relative importance.

On June 27, 1916, we set out from the observatory and went by motor to Honomalino, and thence with horses up the southeast flank of Loa to a point in Kahuku, above Papa, at an elevation of about 6,500 feet above sea-level. Here we made camp on barren ground a little above tree-line on this part of the mountain, close beside a short narrow branch of the new flow—the most northwestern of all its definite branches. The six days, June 28—July 3, we spent in exploration of the source region. On July 4 we returned on horseback to Honomalino and by motor to the observatory.

This camp site was situated on the regular, gentle slope of the mountain dome, between 1½ and 2 miles below the junction of this branch of flow with the rift source. Everywhere here the old surface was of ancient, rusty-red pahoehoe and *a–a* commingled in a complicated pattern—except for an area of gray pahoehoe, younger, but still very old, found about 1¼ miles above camp. Nearly all our way upward from camp to the source led alongside the new flow over slopes below the limits of the great flat above Puu o Keokeo, but as the 1916 source was closely approached these slopes graded into this upland plain west of the new rift cracks.

The sources of all the branches of the 1916 flow lie in the new rift segment. The 1915 rift here is a newly developed fissure, or in most places a very narrow system of closely spaced fissures (the primary group together nowhere more than 30 feet wide and nearly everywhere much narrower) which extends from the northern base of Puu o Keokeo for a distance estimated closely at 3½ miles in a

direction almost exactly magnetic north[1] (see Plate VI, *a*). This fissure, or system of fissures, is practically uninterrupted and, except for a short curving segment at the north end (see Plate VI, *c*), it follows a straight line. It lies wholly within the limits of the great rift zone, but its course is slightly oblique to the general trend of that, which is about N.N.E. (see Plate VI, *b*), and this suggests a major shear through the mountain. It ends on the north at an old red cinder cone at an elevation of about 7,480 feet above sea-level, while at the south its point of interception with Puu o Keokeo is at an elevation of about 6,600 feet (see maps, Plate I and Fig. 1).

Besides this chief rectilinear fissure, or primary group of fissures, there are a great many secondary cracks, running roughly parallel with the system, especially on the west; on the east there are few. Many of these opened *after* the chief outpouring of lava was over, for they traverse the fresh flows. (It is notable, moreover, that earthquakes continued to increase in number and energy until after the eruption began to decline definitely.) Many, however, traverse the older surface neighboring the source; and here they appear as consistent extended fissures in the more or less solid basalt of the mountain, but also there is noted a tendency for the fissuring to be continued from one crack to another through offsets *en echelon* (see Fig. 2).

Though miniature dislocations have resulted necessarily, there is no observable tendency to any general vertical dislocation; but the repeated evidences of offsets *en echelon* strongly suggest a general horizontal shear. There are, however, no sufficiently well-indicated and extended landmarks, surface features, or structure lines to afford a real test or proof of this. Where these cracks traverse the old surface and where they *cut* the new flow, there generally is no evidence of gas outrush, bulging, or fumarolic action, or any evidence of heat emission.

Altogether, as study progressed the conviction gained force that the amount of rending of the mountain dome here seems out

[1] The general magnetic declination in Hawaii is about N. 10° E., but large local variations make the application of corrections so uncertain that the direct magnetic reading is given here by preference.

of all proportion, either to the outrush of imprisoned gas from this vent (for gas emission throughout the flow was apparently small in volume and relatively very quiet), or to the momentum-pressure of the outpoured magma. Also, the features of the rifting and their distribution appear to differ from those that should be expected to result from such causes. (Resemblances of this action to fissure-eruption phenomena in Iceland are noted below. See especially Plate VI, *c*, and Figs. 2 and 3.) Moreover, as just mentioned, great numbers of weak to moderately strong local earthquakes were registered at the observatory 30–35 miles from the source of action, the energy of these *increasing* even after the cessation of forward movements of the flow, but while the vents at the source

FIG. 2.—A panoramic view looking N.N.E., showing the old red cinder cone riven by new cracks, and the solfatara at the head of the new rift (the figures of the men give scale); and black lava, of 1907, at the base of the cone, which is a little over 100 feet high.

were still freely open. Several of these were felt definitely over a considerable area, having a radius of much more than 30 miles; and one or two of these were quite sharp at the observatory. The question of their origin will be discussed in a later paper.

In brief, for many reasons the conception that this eruption was, in part at any rate, *primarily* a *tectonic* event must be examined thoroughly and not put lightly aside. No very violent action was observed or suggested, nor any such as would be expectable were a rift like this to be produced by explosive forces, or by upthrust from a confined substance tending to expand rapidly or seeking immediate outlet to the surface—as volcanic potential usually is

hypothesized. The lips of the rift were not outforced or uplifted, nor were radial cracks produced. Such action of lava and gas outrush as was observed would be expectable if eruption were *permitted* through tectonic rending of the mountain shell in a manifestly weak zone, thus unsettling the physical-chemical equilibrium of the gas-charged magma afforded exit to the surface and the atmosphere in this way. Many of the eruptions of Mauna Loa have exhibited similar peculiarities, perhaps most of those observed. This whole aspect of eruption here deserves a much more thorough discussion than can be given it in this paper. However, to the mind of the writer, the phenomena of the 1916 eruption appear to illustrate admirably the conception so clearly stated by Geikie,[1] if only the expression "tectonic strain" be substituted for his phrase "terrestrial contraction," with the emphasis in this instance on tectonic strain as a cause.

The fact that some of the circumstances of this eruption might be interpreted adversely to this view may be discussed more advantageously in a systematic study of the seismic accompaniment. Altogether this conception deserves careful attention. Of course, it must not be considered to invalidate or displace views developed from, and applied to, other modes of eruption in other lands, but it must not be rejected simply because it is different from them. Moreover, there is no disposition to overlook the very real application of more commonly recognized modes of eruption in this recent outbreak, or in other eruptions in Hawaii. It is intended merely to give this tectonic mechanism emphasis and to point out its possible, or probable, local predominance.

Lava did not well out of the new rift along its whole length. Hence we may subdivide it, recognizing two segments: a longer flow-source segment, and a shorter solfatara-spatter-cone segment stretching on up the mountain beyond the head of flow.

THE FLOW-SOURCE SEGMENT

For about $2\frac{1}{2}$ miles from Puu o Keokeo in a direction about N. 3° W. mag. the new rift is indicated by a system of open fissures straddled by seven double semicones, varying from 20 to 100 feet

[1] *Ancient Volcanoes of Great Britain*, I, 10–13.

in height and from 50 to 200, or more, feet in the length of the greater diameter, built of pumice, cinders, and spatter outfall—these are also primary sources of flowing streams—with many smaller cones and mouths intervening. The resemblances of these cones and fissures, and their interrelationships, to features in Iceland—especially along the great Laki fissure—as described by Geikie[1] and those from whom he drew, and as exhibited in the views by Anderson reproduced by him, is very striking indeed; few would

FIG. 3.—A view looking north into the gash of the second largest cone of 1916, situated a little south of the head of flow. Its character as a double semicone, built of ejected products, and the channel of outflow from the gash are shown. This cone is about 70 feet high.

question that the course of action was similar in both regions (see the photograph, Fig. 3, especially). Moreover, at practically all points along this segment lava welled out and flowed on both sides of the open rift in southeast, south, or southwest directions down along the course of the fissure system and out along narrow, jutting tongues of greater or less length, as well as down the greater streams. One of these, the largest, led toward Kahuku (see the photograph, Plate VI, *d*), and three others led toward

[1] *Op. cit.*, II, 260–65, Figs. 292, 293.

Kona, two of which were relatively small, though not to be mistaken for tongues. Of all these greater streams the Honomalino branch was longest (see the map, Fig. 1).

At its upper end the area of the new flow is narrow, varying in width up to a third of a mile, and elongate parallel to the rift; its margins here are irregular and lobate on a small scale.

THE SOLFATARA-SPATTER-CONE SEGMENT

For a mile above the head of outflow the open-fissure system continues, at first in a direction about N. 3° W. mag., but in its last third it curves gently eastward, so that the direction from the foot of the flow-source segment to the head of this upper segment is N. 2° W. mag. It is marked by an almost continuous line of fresh solfataric action along which, in numerous protected niches, very delicate, feathery, sulphur crystals were subliming in considerable quantity, apparently in unusually pure aggregates (see the photographs, Plate VI, *b*, *c*). This action, and also all conspicuous fissuring, ended in the flanks of an old red cinder cone, whose summit is about 7,480 feet above sea-level and its base 7,375±, which stood directly in the course of the major rift belt not far from its western margin.

Also there were observed along this segment three new spatter cones, the largest 30 to 40 feet in height, wholly isolated from the area of continuous flow; and several small spatter mouths, one of which was situated very near the upper end of the segment at an altitude of 7,370 feet above sea-level.

Near their head the new flows are thin pahoehoe, either in smooth sheets traversed by rift cracks of *later* origin, or, more commonly, broken and torn crusts of pahoehoe transported and piled into an irregular and confused surface (see the photographs, Plate VI, *d*, and Fig. 4). Near the edges of flow, and the edges of festooned flow channels, rough, *a–a*-like textures are seen in all intermediate phases between "pulled" pahoehoe and cindery *a–a*. Down their courses the flows become thicker and their surfaces more irregular and fragmented, passing finally, within a mile or two, through slaggy phases, into unmistakable

cindery *a–a*. These flows spread indiscriminately over the various materials of the old surface and near-by areas of the lava of 1907.

At and near the sources the following types of new lava were observed:

a) PRODUCTS OF FLOW

Pahoehoe, which here exhibits various surface textures determined by the interrelationships of different conditions during the progress of flowing, such as the degree of viscosity (dependent in part upon the temperature, the gas content, its state of solution,

FIG. 4.—A view looking southeast, showing the cone at the head of flow, thin, fresh pahoehoe spread over old pahoehoe and *a–a*, and the south terminal of the line of solfataras. This cone is from 15 to 20 feet high.

the amount of the crystalline content, etc.), the mass, and the gradient of the surface, all these influencing the rate and manner of flow and the consequent action of subsurface traction on the crusts.

Textures

Pumiceous texture, a finely vesiculated spongy surface very closely resembling basaltic pumice in color and structure.

Lacy texture, a more coarsely vesiculated spongy surface modified by flow tractions so as to resemble patterns of complicated lacework.

Ordinary textures, comprising surfaces of varying character and degree of vesicularity, and surface vesicle patterns, difficult to illustrate or describe except at great length, but common in all fields of pahoehoe.

"Pulled" texture, seen in incipiency in the lacy texture, but extended to most of the ordinary types wherever, through continued traction, the surface was greatly sheared after it had stiffened or partially set. This gave rise to stippled and bladed surfaces, and to actually fragmented surfaces, so thus, by degrees, it passed over into a slaggy *a–a* texture.

The textures most prevalent in the source region were the pumiceous texture and the "pulled" texture.

Slag, a product of flow made up of rough fragments varying in size and in character from torn and wrapped pahoehoe crusts to cindery *a–a* lumps.

In a general way, here slag was characteristic of the flow channels near the source and of an intermediate region down the flows between the typical pahoehoe and *a–a* stages.

A–a, rough-surfaced block lava, typical of by far the greater part of all the 1916 branches of flow.

b) EJECTED PRODUCTS

Basaltic pumice in three distinguishable varieties which, of course, grade into each other: (1) a very finely vesicled variety of light-yellow color, almost a thread-lace scoria in structure; (2) ordinary yellow to brown basaltic pumice, with fused surfaces, resembling pulled molasses candy; and (3) a more coarsely vesiculated brown to black pumice which grades with the increasing size and the decreasing numbers of vesicles into

Cinder lumps, which, in turn, grade with decreasing vesicularity and increasing density into

Slag lumps, (1) some of which exhibit a surface like obsidian; (2) others a surface like *a–a*.

All these were observed all along the rift and about the spatter cones, but the pumice phases were very abundant near the south

end and around the major cones (see the photograph, Plate VI, *d*), while slag lumps were more characteristically found about the spatter cones and along the northern part of the rift course.

Also there was suggestion that the ejection of slag lumps continued after the action of pumice ejection was over, but no *proof* of this could be elicited.

DISTANT OBSERVATION OF THE UPPER SOURCE

The upper source of the 1916 eruption, where the outbursts of fumes occurred on May 19, has not yet been visited, so far as the writer is aware. This is a place on the great mountain dome very remote from trails, and travel with horses over the barren, untracked lava is both difficult and dangerous. This source lay between 13 and 15 miles from our camp—a distance altogether too great to cover on foot in the short time at our disposal over going so rough as that prevailing within and along the rift belt.

However, this region could be seen plainly through the clear mountain air from the old cone at the head of the lower rift, at a distance of a little over 9 miles. With binoculars magnifying eight diameters some of its characteristics could be made out. It lay within, and was much elongated parallel to, the axis of the major rift zone. It extended from near the edge of the summit plateau down the somewhat steep upper slope nearly to the great flat which lies north of Puu o Keokeo. It appeared to have a moderate breadth, say a quarter of a mile. Fumes were clinging, or slowly rising, along its axis, probably from a system of fissures (see the photographs, Plate VI, *a* and *b*). In two places, apparently not far apart, about two-thirds of the way up its course, definite columns of rising fumes could be made out frequently. On one occasion, in the late forenoon of July 3, one of these columns was estimated to reach upward 500 feet before it spread out and dissipated.

At all times when it was clearly visible the surface of this source area, on both sides of the line of fumes, appeared of very light color, even whitish. It could not be determined whether this was due to the sheen of new pahoehoe, to efflorescence of sulphur or

sulphur salts, or to the escape of fumes in very small quantity from numerous cracks distributed over the area. No other explanations of this light color suggested themselves.

Cones of medium size could be seen within the area. Fumes were rising from them and around them. It is uncertain whether these were new cones, or old cones freshly riven. In general, here, eruption does not take place through old fissures reopened; but exceptions are known. There was no great amount of action at night at this upper source. However, the fuming action in the cleft and on the sides of one of these cones strongly suggested that it was of new origin.

Certain features of older origin, found in the neighborhood of the lower source, claim bare mention here.

Above Puu o Keokeo there is a long, narrow flow of fresh, black *a–a* (with long narrow tongues projecting from it over the great flat to the eastward), which stretches along the eastern margin of the 1916 flow source, and in part lies under the 1916 outflow. This begins much farther up the mountain, in the course of the rift, than the 1916 head. Undoubtedly this is lava of 1907, and it is mapped by Baldwin as of this date (see the map, Plate I). However, on his map it is shown as extending down past Puu o Keokeo on the *east* of that group of cones. Nevertheless, on the writer's short reconnaissance he went on horseback up between the flow of 1887 and the Kahuku branch of 1916 onto the ancient lava ridge that projects uninterruptedly eastward from Puu o Keokeo without crossing this lava stream. Hence it is clear that no part of this flow follows the course past Puu o Keokeo shown on that map. This upper stream did, however, pass down on the *western* side of Puu o Keokeo. While the detailed expression of its course, therefore (and of that of a contributory stream from a source below Puu o Keokeo), must await adequate topographic survey, the writer has *diagrammatically* sketched its course on the west of Puu o Keokeo on the map, Fig. 1, showing these southwestern flows. However, he has not attempted to indicate the long tongues which project southeastwardly over the great flat north of Puu o Keokeo, on account of want of data, and of the cartographic confusion that might result.

The 1916 eruption was of small magnitude compared with earlier action originating near its source. There are accumulations of ancient pumice far greater in depth and spread than that ejected at this time. The older double semicones round about are higher and greater and their gashes and fissure systems on a larger scale.

One such ancient source—whimsically designated in field notes as "the lunar crater" because of a steep and relatively high peak of riven blocks which stood near the center of its large, circular depression, or crater-like area—had been the spring of a lava flood *vast* in proportion to the recent flow. All about this old depression, except for its gap at the south, was a high rampart built of huge cinder blocks piled confusedly, and outward from the top of this a slope built of small cinders and pumice fragments fell away gradually.

Also the cones at Puu o Keokeo point to action of far greater magnitude at the time of their building than recently—greater than any action of historic date on the south flank of the mountain. These cones, however, are only a conspicuous group in the well-marked belt extending from the summit down the slope below them. Though perhaps these are the largest of all, there are others of comparable size, both above and below. The suggestion, therefore, attributed to the late S. E. Bishop, that Puu o Keokeo is a vent distinct from Mauna Loa, but subordinate to it, probably must be dismissed. This point, though a digression, is interesting and important, since it might be considered to bear on the question of the genesis of the 1916 eruption.

In connection with this same point it is worthy of note that the eruptions of 1868 and 1887 (and probably of 1907 also) were preceded by outbreaks of fumes and lava much higher up the mountain than their eventual heads of flow—action similar to that preceding the 1916 flow.

In 1868 such action broke out in the evening of March 26, with a further outburst in the early morning of March 27 "a little to the southwest of the summit," followed by outflow from low sources, at the southwest on Kilauea on April 2, and at the south-southwest on Mauna Loa on April 7. This upper outbreak was very near the summit.

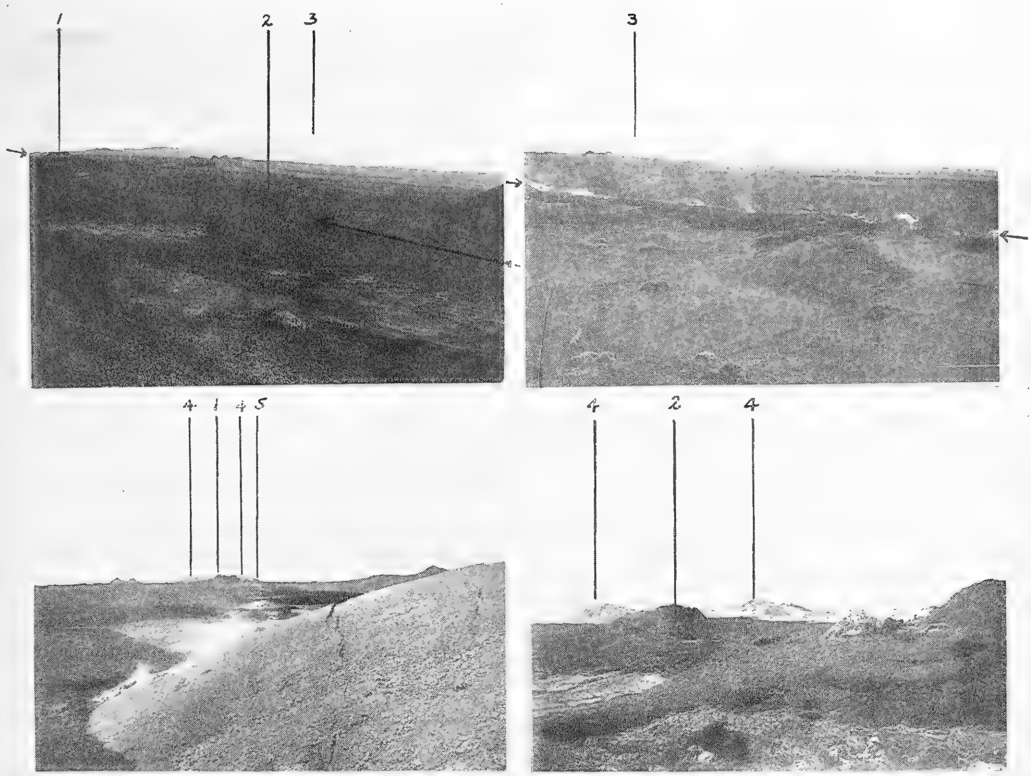
In 1887 the first outbreak was in the evening of January 16 at an elevation of about 11,500 feet on the southwest, and flow began, from a little below Puu o Keokeo, in the evening of January 18.

The exact places of these upper outbreaks were not mapped in either instance.

In 1907, on account of weather conditions adverse for distant seeing, only vague accounts were given. Nevertheless, mention is made, perhaps doubtfully, of an outbreak judged to be at the summit, preceding by a few hours the outbreak of flow lower on the flank.

Hence, though the places of outflow in several of these eruptions have been found suggestively near to Puu o Keokeo, still there is no doubt that the eruptive action in all cases extended far up the south flank of Mauna Loa beyond this group of old cones. Moreover, critical study of the distribution of these heads of flow develops no causal association with this as a center.

a *b*



c *d*

a, a view looking a little to the north of east from Puu o Keokeo, showing the flow source. The new rift line, indicated by arrows, traverses the middle ground obliquely. Note the gashed cones; also note the faint streak of fumes, line 3, near the mountain summit, 14–15 miles away—the source of the fume outburst of May 19. Line 1 indicates the larger cone at the chief head of the Honomalino stream. Line 2 indicates the largest 1916 cone at the chief head of the Kahuku branches.

b, a view from an old cone a little N.W. of the head of *flow* looking about N.E. at the northern portion of the new rift, indicated by short arrows at margin, marked by solfataric action. Note also the streak of fumes, and the light-colored area, at the source of the outbreak of May 19, line 3.

c, a view looking south toward Puu o Keokeo from the old cone at the head of the new rift. Note the slight curve in the line marked by solfataric action, with new cones beyond; line 1 indicates one of the larger new cones at the chief head of the Honomalino stream, line 5 indicates the small cone at the head of *flow*, and the lines 4 indicate Puu o Keokeo, $3\frac{1}{2}$ miles away. In the foreground is a freshly riven spur of the old cone.

d, a view from near the eastern edge of the new flow, looking S.S.W.—a detail of the source near its southern end, showing the cone at the head of the Kahuku branches; line 2, a short tongue of 1916 lava projecting eastward, and old surface in the foreground. A considerable fall of new, basaltic pumice partly covers both old and new lava here. The lines 4 indicate Puu o Keokeo.

A PROPOSED DIP PROTRACTOR

CHESTER K. WENTWORTH
University of Chicago

The device herein described consists of a celluloid chart giving the dip of any plane along a line at any given angle with the strike. Several tables for this purpose have appeared which, for office work, are entirely satisfactory. The protractor has in a certain class of

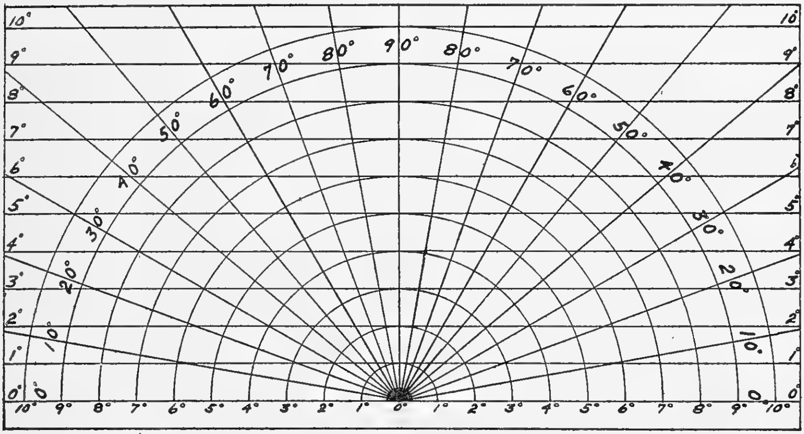


FIG 1.

fieldwork, which will be outlined below, a superiority over the tables and has not, so far as I am aware, been before described.

The protractor consists of a rectangular plate of transparent celluloid ruled and numbered as shown in Fig. 1. The circular curves represent each a given angle of dip of the plane, i.e., the maximum angle commonly denoted dip. The intersection of the appropriate curve with the radiating line of direction of the required dip cuts off an ordinate, or distance from the horizontal

diameter line, the value of which in terms of the vertical scale at the side is the required angle of dip.

As an example, let it be required to find the angle of dip in a direction 40° from the strike, of a plane of which the maximum dip is 5°. Following the 5° curve to its intersection with the 40° radial line and interpolating this point between the 3° and 4° parallel lines we find the value of approximately 3°15′ which is the desired angle of dip.

The particular field of usefulness of this device is in projecting the plane of a given stratum whose dip and strike are known from a plane table set up on the outcrop. We have in this case the dip and strike of the plane and the direction of the line of sight for which we wish the dip. The horizontal diameter line of the protractor is laid parallel to the strike as recorded on the oriented plane-table sheet and the alidade set on the required line of sight with its edge passing through the center on the protractor. At the intersection of the ruler edge with the appropriate dip-curve is read the required angle of elevation or depression to be set on the telescope to project the plane. This graphic solution of the problem in the field and directly on the plane table is much more rapid than a combined protractor and dip-table solution and is sufficiently accurate for reconnaissance and mapping purposes where projecting the outcrop on topography is the "best guess" the field man has in many instances.

The protractor as shown is made only for angles up to 10° because occasions for projecting dip in cases of higher dips are much more rare and correspondingly less accurate, and greater accuracy for the low angles is attained by putting fewer lines on the celluloid. The radii of the several dip circles are constructed proportional to the tangents of the respective dip angles, as is also the spacing of the parallel horizontal lines which are tangent to them. Thus if A is the nominal dip of any plane, B the required oblique dip, and C the angle of obliquity, we have

$$\sin C = \frac{\tan B}{\tan A}$$

and a circular arc may be used for the dip-curve. For the low angles as shown on the protractor in Fig. 1 the tangents are so nearly proportional to the angles that the spacing intervals depart from equality by an inappreciable amount only. There should be no difficulty in reading required dip angles to the nearest two or three minutes of arc with the protractor as shown, and several protractors might provide for the whole range up to ninety degrees for those requiring the higher angles.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Abendanon, E. C. *Considérations sur la composition chimique et minéralogique des roches éruptives, leur classification et leur nomenclature.* La Haye, 1913. Pp. 34.

Andersen, Olaf. "The System Anorthite-Forsterite-Silica," *Amer. Jour. Sci.*, XXXIX (1915), 407–54.

A description and discussion of experimental methods used, and results obtained, by fusing quartz, alumina, calcium carbonate, and magnesia. Solid phases of anorthite, forsterite, cristobalite, tridymite, clino-enstatite, and spinel were observed, and their thermal and optical properties determined. Anorthite and silica form a simple eutectic system, forsterite and silica form a system with an unstable compound, while anorthite and forsterite form no true binary system. The application of the results to igneous rocks is pointed out.

Arschinow, W. W. *On Inclusions of Anthraxolite (Anthracite) in Igneous Rocks of Crimea.* Petrographical Institute "Lithogäea," Publication No. 4. Moscow, 1914. Pp. 15. (In Russian language.)

The term anthraxolite, originally proposed by Chapman for anthracite found associated with quartz and pyrite in certain veins in the Lake Superior region, is used by Arschinow for all bituminous substances. Such substances occur in the form of small, black inclusions in igneous rocks in two places on the southern shore of the Crimea. Since it also occurs as vein and cavity fillings in the rock, and in many cases is associated with calcite and quartz, it was probably formed, after the cooling of the magma, by the destructive distillation of bituminous substances disseminated in the stratified rocks.

Ball, Sydney H., and Shaler, Millard K. "Contribution a l'étude géologique de la partie centrale du Congo belge y compris la région du Kasai," *Ann. soc. géol. Belgique*, 1913, 199–247, map 1, pl. 3.

The writers found diabase, granite, diorite-gneiss, granitoid-gneiss, chlorite-schist, and amphibole-gneiss in this region.

BECK, KURT. "Petrographisch-geologische Untersuchung des Salzgebirges an der oberen Aller im Vergleich mit dem Stassfurter und Hannoverschen Lagerstättentypus," *Zeitschr. f. prakt. Geol.*, 1911, pp. 23, figs. 6, pl. 1.

Discusses the sequence of deposition and the characters of certain salt deposits, and compares them with the well-known deposits in Stassfurt and Hannover.

BECK, KURT. "Petrographisch-geologische Untersuchung des Salzgebirges im Werra-Fulda-Gebiet der deutschen Kalisalzlagerstätten," *Zeitschr. f. prakt. Geol.*, XX (1912), 133–58, figs. 12, pls. 2.

Discusses the stratigraphical and structural relationships of the salt deposits of Werra and Fulda.

BEGER, P. J. "Zinnerzpneumatolyse und verwandte Erscheinungen im Kontakthofe des Lausitzer Granits," *Neues Jahrb. Min., Geol., und Pal.*, 1914 (II), 145–82, figs. 4, pls. 2.

The writer discusses the contact zone of the Lausitz granite, describes various pegmatites, greisens, etc., and concludes that the chlorite in the highly metamorphosed greywacke is a pneumatolytic mineral due to the adjacent granite.

BENSON, W. N. "The Geology and Petrology of the Great Serpentine Belt of New South Wales" (in five parts), *Proc. Linnean Soc. New South Wales*, XXXVIII (1913), 490–517, 569–96, 662–724; XL (1915), 121–73, 540–624; maps 6, figs. 29, pls. 10.

The region described in these papers passes north and south through Tamworth, and lies between Sydney and Brisbane, about 280 miles from the former. Through the center of the region extends a north-and-south fault, separating it into two portions. Along this fault is a series of intrusions of rocks now serpentine, not continuous but forming separate patches from 100 yards to 30 miles in length and from a few inches to nearly two miles in width. The formations indicate that after a long period of sedimentation heavy orogenic pressure came from the east, folding and metamorphosing the eastern series, but having less effect on the western. The pressure caused the formation of an overthrust fault which became the channel for the ascent of certain

basic rocks. The sedimentary formations, which prior to the folding had a thickness of over 30,000 feet, are described, and a list is given of the fossils found.

The igneous history begins in Lower Devonian times with the extrusion of spilitic lavas and tuffs. In the Middle Devonian similar rocks attain a thickness of over 7,000 feet, and associated with them are 2,000 to 3,000 feet of intrusive dolerite, in many cases albitized. In Upper Devonian times some 3,000 feet of agglomerates were formed, and, after a long period of quiet, rhyolites, andesites, and tuffs appeared in the Lower Carboniferous. The intrusion of the peridotites then followed, chiefly along the fault line previously mentioned, and probably during the crust-movement at the close of the Carboniferous. Gabbros and eucrites came later than the serpentine, and cutting these are dikes of dolerite. From latest Carboniferous to early Mesozoic times came a long series of granitic intrusions consisting of granodiorites and porphyries, and titanite-, tourmaline-, and other granites. Besides these rocks there are numerous lamprophyres whose time period was not determined. Following the Permo-Carboniferous was an era of great crumpling, then followed a long period of erosion which exposed the granite, and then a later period of sedimentation. During Tertiary times the formations were largely volcanic, and thick flows of basalt occurred. A great period of elevation and block-faulting closed the Tertiary.

The second paper deals with the geology of the Nundle District, and the third with the petrology of the entire region. Various rocks are described: spilites, used in the sense of Dewey and Flett for lavas with sodic feldspars, contain acid oligoclase and augite with some secondary chlorite and epidote and with or without magnetite; the so-called "keratophyres" are composed almost entirely of acid oligoclase with some interstitial chlorite from augite; the dolerites consist of plagioclase (andesine to albite), augite, magnetite, with a little quartz and various accessories, and are medium-grained. The term dolerite is apparently used in a different sense from that common in the United States, where it signifies a coarse-grained basalt containing a basic plagioclase. The writer speaks of albitization proceeding inward in the feldspars, by which he means, apparently, that the sodic rims are secondary. It would seem more probable that the zonal rims are primary. The rock thus appears to be an augite-andesite. The peridotites are chiefly harzburgites, but there are local occurrences of dunite and lherzolite. With the absence of olivine, enstatolites occur. Associated with the

peridotites and pyroxenites are rarely amphibolites and olivine-gabbros, more commonly eucrites and anorthosites. The silicic rocks described are felsites, granodiorites, and various granites. Malchites, granite-porphyries and quartz-porphyries, and minettes, vogesites, and camptonites occur as dikes.

Twenty-two analyses are given of rocks of this region, unfortunately showing a number of typographical errors and errors in proof-reading owing to the absence of the author from the state during the passage of the paper through the press.

The fourth paper deals with the dolerites, spilites, and keratophyres of the Nundle District. In this the statement is made that the feldspar of the keratophyre is pure albite and not acid oligoclase, as stated in the earlier paper. The spilites, dolerites, and keratophyres all appear to be intrusives in the sediments. Certain of the spilites, in the opinion of the author, were intruded into soft mud, for they show a pillow structure. Most of the rocks are rich in primary albite.

The fifth paper is on the geology of the Tamworth District. A series of radiolarian claystones was deposited at shallow depths on a steadily sinking sea-floor in Devonian times. There were two periods of volcanic activity, and masses of tuffs and agglomerates accumulated in the sea, and spilites, dolerites, and keratophyres were intruded. The total thickness of the series is unknown, but apparently about 12,000 feet are Middle and Upper Devonian. Faulting and folding took place in the Carboniferous period, followed by peridotitic intrusions, and later by intrusions of granite. A final eruption of basalt occurred in the Tertiary period.

BERKEY, CHARLES P. "Petrographic Range of Road-Building Materials," *School of Mines Quart.*, XXXV (1913), No. 1, pp. 6.

BLANCHARD, RALPH C. *The Geology of the Western Buckskin Mountains.* Dissertation. Columbia Univ., 1913. Pp. 80, numerous figs.

BOEKE, H. E. "Bemerkung über die Theorie von J. Johnston bezüglich des Verhaltens fester Stoffe unter ungleichförmigem Druck," *Centralbl. f. Min., Geol., u. Pal.*, 1913, 321–24.

BOEKE, H. E. "Die Methoden zur Untersuchung des molekular Zustandes von Silikatschmelzen," *Neues Jahrb. Min., Geol., u. Pal., B.B.*, XXXIX (1914), 64–78.

BOEKE, H. E. *Grundlagen der physikalisch-chemischen Petrographie.* Gebrüder Borntraeger, Berlin, 1915. Pp. xii+428, figs. 168, pls. 2.

In view of the important bearing of recent physico-chemical research upon the problems of the origin of igneous rocks, this work is most timely and acceptable, and is to be recommended to all advanced students of petrology. It is an invaluable summary of work already done, and contains many suggestions for future work.

The author not only presents the results of previous work but describes in detail the methods and apparatus by which these results were obtained. The subject is presented in a very clear and orderly manner, and as simply as is compatible with the nature of the subject. In his treatment the author follows the inductive or synthetic method, that is, he describes first the behavior of the simplest constituents of rocks under known conditions of composition, temperature, pressure, time, etc., and compares the results with those found in nature. Beginning with the magma, he traces it through all stages of cooling and through the gradual changes which take place in its solidification products.

In older petrologic textbooks there is a great variety of views as to observed phenomena, primarily because so many factors must be taken into consideration, and one or another may predominate. Since in many cases there are more unknown than known factors, a single solution may be impossible. The synthetic method seeks to determine, by exact and systematic investigation, the action of each factor, such as temperature, pressure, capillarity, etc.

In most provinces of petrology only the beginning of inductive research has been made, and the experimental work so far is no more than a groping after the truth. Little can be said at the present time as to the formation of rocks from their complicated magmas, and physical chemistry can not yet settle such questions as the origin of magmatic differentiation, the relation between the alkali and alkali-lime rocks, and that of dike satellites to parent rock, etc., on account of the lack of reliable data.

The present text is so comprehensive that only the very briefest outline of the contents of the various chapters can be given; a list of the

subheads alone would require five or six pages of this Journal. After a short discussion of homogeneous and heterogeneous equilibria, the subject of magmatic rock-formation is taken up. Under this head the author treats of the essential components of magmas and the melting-points of minerals, and includes a discussion of various methods of determining melting-points and of obtaining and measuring high temperatures in the laboratory. He speaks of the alteration of melting-points at different pressures, of uniform and non-uniform pressures, and of overheating and undercooling. Under the properties of silicate melts are included internal friction and diffusion, surface-tension, electrical conductivity, influence of gravity and centrifugal force upon the composition of melts, measurements of density at high temperatures, etc. Following a chapter on the inversion points of minerals, he discusses the genetic significance of melting- and inversion-points in rock-forming minerals. He describes two, three, four, etc., point systems, and then devotes about seventy-five pages to the physico-chemical, especially the thermal, properties of the more important rock-forming minerals.

In the second division of the book the author takes up the gases in magmas—their nature, their solubility in melts, and their equilibrium. In the third division he treats of the pegmatitic, pyrohydatogenic, and hydrothermal phases of the solidification of magmas. Here are included the properties of water at high temperatures, and a general discussion of the formation of minerals in systems with volatile components. Then follows a chapter on the synthesis of pneumatolitic and hydatogenic minerals; then hydrothermal synthesis, solubility of the common products of hydrothermal mineral-formations, alteration with temperature and pressure of salts which are but slightly soluble, the relationship of solubility and size of grain, succession and paragenesis of the hydrothermal ores and vein-minerals, zeolites, etc.

The fourth division is devoted to weathering or colloid mineralogy; the fifth to sediments. Here is included a long discussion of salt deposits (43 pp.) to which the author has devoted considerable study. The book closes with a short chapter on metamorphism and a double column index of 26 pages.

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—DALY, R. A. Problems of the Pacific Islands. [American Journal of Science, 4th Series, Vol. XLI, No. 242. February, 1916.]

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STRUCTURE OF THE ANORTHOSITE BODY IN THE ADIRONDACKS

H. P. CUSHING
Western Reserve University, Cleveland, Ohio

Introduction.—In No. 3 of the current volume of this *Journal* Dr. N. L. Bowen has discussed "The Problem of the Anorthosites" in a very suggestive and important paper with whose general thesis I find myself in quite hearty accord. It seems to me that the process of formation of anorthosite, as there outlined, is quite the most probable method yet suggested; and I am quite in agreement with the explanation of the general protoclastic and granulated textures which all large bodies of anorthosite exhibit.

When, however, Dr. Bowen comes to consider the universal, or usual, field relations between anorthosite and the accompanying bodies of syenite, and suggests in that connection a structural relationship of these rocks in the Adirondack region, the field facts there, as known to me, seem to be in direct conflict with certain features of that suggestion. The chief point on which we differ does not seem to me in any way to vitiate his main argument, but it does seem desirable to bring it out plainly.

His argument is substantially as follows: that there is (*a*) an intimate connection of syenite with anorthosite wherever the latter is found, as shown by the abundance of rock types intermediate

between the two and by the rarity of exposures showing an intrusive relation of the one with the other; (*b*) an intimate association of syenite with Grenville in many places, as contrasted with the anorthosite areas which are comparatively free from Grenville inclusions; also (*c*) the frequent occurrence of Grenville beds overlapping syenite in moderately undisturbed fashion, after the manner of a roof.

Because of the latter relation Bowen argues that it is difficult to picture the syenite and anorthosite as conventional batholiths. He says:

> It is necessary to imagine an early intrusion of a huge plug of anorthosite, followed by an intrusion of syenite which took the form of a hollow cylinder, circumscribing it and invading it only peripherally. All this must take place without throwing the Grenville series into appressed folds, indeed without significant folding of any kind. It is then necessary to imagine that erosion removed every vestige of a roof from the small, interior anorthosite area, and left great stretches of it throughout the broad syenite-granite belt that surrounds it.[1]

Because such relationships seem to him improbable he suggests that the Adirondack eruptive complex consists of a sheetlike mass, or huge laccolith, with syenite overlying anorthosite.

The purpose of this rejoinder is to point out that we are not limited solely to the two alternatives outlined above, and that the data obtained in the field seem to me definitely to contradict the hypothesis that the Adirondack region is composed of a single great sheetlike mass, with syenite overlying anorthosite and bearing all the Grenville exposures of the region rooflike on its back.

Distribution of anorthosite and syenite.—The Adirondack anorthosite is massed in a single great body, rudely heart-shaped, with the apex toward the south. There are a number of small, outlying masses, some of which have some bearing on the questions under discussion. But in addition the continuity of the main mass is interrupted by two considerable *inlying* bodies of other rock, one in the Lake Placid region and one near Keene. Both of these are shown on the state map. At the time when Kemp prepared this

[1] *Jour. Geol.*, XXV, No. 3, 223.

portion of the map we were just beginning to recognize the green syenite of the region as a later intrusive and to separate it from the main body of the gneiss in mapping; hence comparatively little syenite is shown as such on this map, and much of what is there mapped as gneiss has been since shown to be syenite also. The two inliers referred to are mapped as gneiss; but Kemp's description of the rocks clearly shows that the Placid inlier consists largely or wholly of syenite and that the same rock is represented in the Keene inlier.[1] Both of these inliers are entirely surrounded by anorthosite, and lie well within the mass.

By comparison with the anorthosite the syenites occur in separate masses of smaller size, usually much smaller, and there is a large number of such masses. Some of these directly border the anorthosite, but there is nothing like a continuous rim of syenite about it. These syenite masses range throughout the entire region and, in my experience, are no more abundant near the anorthosite than they are away from it. The anorthosite lies in the eastern portion of the Adirondack pre-Cambrian, and its relationships to other rocks on its eastern margin are largely hidden by down-faulting and by the cover of Champlain Paleozoics. But to the west and south abundant syenite ranges away to distances of 60 or 70 miles beyond the anorthosite border; and such pre-Cambrian outliers as those at Little Falls and Middleville bear witness that it runs an unknown distance beyond the pre-Cambrian margin under the Paleozoic cover.

The point here made is that the syenite is spottily distributed over the region, is no more abundant near the anorthosite than it is away from it, and extends so far from the surface exposures of anothorsite that the latter must be given an enormous lateral extent underground, on the supposition that the two constitute a sheetlike mass, with the anorthosite beneath. It is candidly admitted that this point has no particular value if Dr. W. J. Miller's conception of the constitution of the Adirondack pre-Cambrian complex is the correct one. His view is that this complex consists entirely of a foundation of intrusives of the anorthosite-syenite-granite group, upon which fragments of the Grenville

[1] *Bull. 21, N.Y. State Mus.*, pp. 55–56.

cover locally persist.[1] My view is that a complex of Grenville, resting on orthogneiss, existed in the region at the time of the intrusion of the anorthosite-syenite group, that much of this orthogneiss still remains in the region, and that the later intrusives broke through this complex in separate masses, instead of forming one great body.[2] Obviously the presence of a great laccolith constituting the entire region, such as Bowen postulates, is much more possible under the former view than under the latter.

It is quite true that many of the syenite masses are much mingled with Grenville and that the anorthosite area contrasts rather sharply in this respect, as Bowen contends. And I am quite in accord with his view that there has been deeper erosion in the eastern Adirondacks, where the anorthosite occurs, than there has been to the west and south, where the syenite bodies occur, and have repeatedly so stated. Nor am I particularly disposed to quarrel with the view that the anorthosite mass may be laccolithic instead of batholithic in structure. I do not know which it is. The mass has certainly great thickness, since the climb up Mt. Marcy furnishes a 3,500-foot section of pretty clean anorthosite, with no particular indication that the entire thickness may not be vastly greater; then allowance must be made for at least an equal thickness of gabbro and pyroxnite underneath and for an unknown thickness of overlying syenite, since eroded away. Nevertheless, a sheet structure is entirely possible.

Differentiation of the anorthosite body.—If I have correctly understood Dr. Bowen's interpretation of the structure of the region—a sheetlike igneous mass, composed of probable gabbro below, then anorthosite, and finally a cover of syenite and granite, the cover full of fragments from the Grenville roof, and with a certain amount of disturbance occurring during the freezing of the mass, whereby liquid syenite is brought into lateral contact with solid anorthosite—his argument seems to me to imply, or to require, that this sheet was at least equal in size to the present pre-Cambrian area of northern New York and that anorthosite must everywhere underlie syenite. The field evidence, however, seems to me to

[1] *Bull. Geol. Soc. Am.*, XXV, 243–64.

[2] *Am. Jour. Sci.*, XXXIX, 288–94.

demonstrate that the full girth of the anorthosite intrusion is represented by the dimensions shown on the present maps and that the outlying syenite bodies represent distinct and slightly later intrusions.

Dr. Bowen[1] discusses the "Intimate Relation of Syenite and Anorthosite" and makes the following statement:

> This aspect of the anorthosite, i.e., its intimate connection with the syenite, is emphasized in the area as a whole, where, in spite of fairly good exposures, only one other locality showing the intrusive relation of syenite to anorthosite has been found, but where, on the other hand, types intermediate between the two are rather commonly found.

It is chiefly these two points of his paper which I wish to discuss, since my field experience is quite antagonistic to them. I have myself published several localities where dikes of syenite cut the anorthosite, and on the next page of his paper Bowen quotes W. J. Miller as authority for the statement that dikes of syenite cutting anorthosite occur in the Placid region. My thesis is that the general differentiation *in situ* shown by the anorthosite is into anorthosite-gabbro and gabbro, and not into syenite; that such intermediate rocks as do occur are chiefly intermediate between syenite and gabbro, instead of between syenite and anorthosite; and that the demonstrable source of these latter intermediate rocks in many cases, if not in most or all of them, is assimilative attack of a later intrusion upon an earlier, and is not differentiation *in situ*.

The boundary of the anorthosite is in part along faults. Where unfaulted the anorthosite is always found to grade into anorthosite-gabbro, and this into gabbro as the boundary is approached. This change is depicted upon the Long Lake and the Elizabethtown quadrangle maps and occurs also in all other parts of the region in which I have any acquaintance with the boundary. Daly has interpreted this as a chilled border of the anorthosite, and in my judgment this is not only the most reasonable, but in fact the only satisfactory, explanation that can be made of it.[2] If this be true,

[1] *Op. cit.*, p. 211.

[2] *Igneous Rocks and Their Origin,* p. 240.

it follows of necessity that the anorthosite is a differentiate *in situ* from a gabbro intrusion *and that the chilled border determines for us the original size of the mass* at the depth represented by the present erosion surface—in other words, that this particular anorthosite mass cannot be regarded as spreading out underneath the outlying syenite masses and extending throughout the region. If it be argued that the anorthosite body, while cooling, developed a syenite cover, since removed by erosion, I would state that I think this very probable, and would even go so far as to suggest that the Placid and Keene inliers of syenite may be remnants of this cover. If so, it would be in their vicinity that true transitional rocks between syenite and anorthosite would be most likely to occur. Whether they so originated, or represent plugs of syenite rising through the anorthosite, can be determined only in the field with aid of favorable exposures, if any such exist. But even this gives no aid in explanation of the outlying syenite masses.[1]

The syenite-anorthosite boundary across the Long Lake quadrangle suggests intrusive attack of syenite upon anorthosite for its entire length. Along it the syenite develops a basic border of its own, which I have elsewhere endeavored to show is due to assimilation of gabbro and anorthosite gabbro by the molten syenite.[2] In places the syenite thrusts deep salients into the anorthosite, and an excellent sample may be seen on the Long Lake map, coming down to the Raquette River just north of Raquette Falls. It cuts into the anorthosite body to a depth of two miles, cutting out much of the gabbro and anorthosite-gabbro border, though these appear in full width on both sides of the salient. Within it are several inclusions of anorthosite gabbro, five of which are of sufficient size to be delineated on the map. Each inclusion has an aureole of very basic syenite, grading away imperceptibly into the normal rock. These are remnants of the anorthosite-gabbro border which was there before the syenite salient was thrust in, and which has escaped the utter digestion experienced by the remainder.

[1] It should be noted that the transitional antiperthites described by Bowen are from the Placid region (*op. cit.*, pp. 221–22).

[2] *Bull. Geol. Soc. Am.*, XVIII, 477–92; *Bull. 115, N.Y. State Mus.*, pp. 478–82.

In addition the anorthosite is cut by dikes of syenite in several localities, some of them four or five miles in from the anorthosite border. The field evidence seems clear that the anorthosite had solidified, with a chilled border, and had then been attacked from the side by a mass of molten syenite, which in places cut deeply into it. Along the contact a basic border phase of the syenite was produced, which is not a chilled border *because found only along that part of the syenite boundary which is in contact with the anorthosite*, and hence must be due to the assimilative incorporation of anorthositic material. The product is an intermediate rock, but intermediate between syenite and gabbro rather than between syenite and anorthosite. It differs from the normal syenite chiefly in its large content of ferromagnesian minerals rather than by pronounced difference in the character of the feldspar. It somewhat resembles the gabbro, but ability to distinguish the two is quickly attained in the field.

Dr. Bowen's suggested interpretation of these relations is that disturbance occurred during solidification of the sheet-like mass, after the anorthosite had become practically solid, but while the overlying syenite was still fluid, faulting the one against the other and thus permitting the fluid to laterally attack the solid, giving rise to the intrusive features found in the field. This is a possible cause of such relationships, but it seems to me that the presence of the chilled gabbro border of the anorthosite is fatal to its application in this particular case. That border seems to me to indicate that this is the original size of the anorthosite mass; that it cannot therefore extend westward underneath the bordering syenite; that it cannot possibly underlie the great number of other syenite bodies which range away for distances exceeding 50 miles to the west and south.

The presence of anorthosite outliers in the region somewhat complicates the problem, and might be thought to lend support to Bowen's conception of the structure. The largest of these known to me is that at Rand Hill, Clinton County, which I described years ago. This lies 20 miles distant from the nearest part of the main body, at Keeseville, and seems to me to represent a distinct intrusion, though in all probability an offshoot from the same

parent-mass below ground. The other known outliers are all small, are all composed of anorthosite gabbro, lie within a distance of 10 miles from the anorthosite boundary, and are either demonstrable or probable inclusions in the syenite or else are dikelike or pluglike offshoots from the main mass. So far as I know the evidence, they do not at all require belief in the greater extent of the anorthosite mass underground.

Conclusion.—While, therefore, I am quite in accord with Dr. Bowen in the belief that the gabbro, anorthosite, syenite, and (in part) granite bodies of the Adirondacks are all differentiates from a common parent-magma and are closely akin in age, I do not believe that the present surface exposures can be successfully explained as constituting one great igneous body. The anorthosite mass arose to its present position as a gabbro magma, developed a chilled border, differentiated with production of anorthosite and quite possibly overlying syenite, and solidified. The overlying syenite has since been eroded away, except for the possibility that the Placid and Keene inliers may represent portions of it. In so far I can follow Bowen without trouble. But to account for the outlying syenite and granite bodies away from the anorthosite I think that we must resort to the conception of at least one other body of magma, probably of several others, which went through a similar differentiation well below the present surface and from whose upper parts bodies of molten syenite were pushed upward. Some of these came up along the margins of the solidified anorthosite mass while it was still hot and produced the contact relations which we find today.

It is not safe to say, at the present time, that the floor of the entire Adirondack region is constituted of representatives of this one igneous group. It is quite true that the Grenville remnants in the region always rest on igneous rocks which bear an intrusive relation to them. But in my view there are considerable masses of orthogneiss present much older than the rocks of the anorthosite-syenite group; in places the Grenville rests on these, and it is not at all certain that they rest on the younger intrusives; and in many parts of the region these rocks border the anorthosite, as, for example, along Cold River on the Long Lake quadrangle. The

conception of a cylinder of syenite enfolding anorthosite is therefore neither a necessary nor a true one; rather, there are a number of separate syenite masses.

ADIRONDACK INTRUSIVES

N. L. BOWEN
Geophysical Laboratory, Carnegie Institution of Washington

In his paper on the "Structure of the Anorthosite Body in the Adirondacks" Professor Cushing offers some objections to the interpretation of Adirondack igneous geology that was given by me in the paper "The Problem of the Anorthosites," and he has kindly asked me to comment upon his objections. It naturally gives me considerable satisfaction that an investigator with Professor Cushing's broad experience of Adirondack geology should accept the more important and vital aspects of my interpretation of the genesis of Adirondack igneous types. I therefore find myself disinclined to object very vigorously to his remarks on features of Adirondack structure concerning which he finds it necessary to disagree with me. This is especially true since it would be presumptuous on my part to differ from him on any point involving actual knowledge of field facts. Nevertheless, there seem to be certain questions of interpretation on which there is room for alternative views.

The common, basic border phase of the anorthosite Professor Cushing considers fatal to the idea of the extension of that rock type laterally as a sheetlike mass beyond the limits of its present exposure. He accepts Daly's interpretation of this border phase as a chilled portion and considers that this phase must be the outer limit of the anorthosite. I, too, accept Daly's interpretation of the basic border, but consider that it is not necessarily an outer limit; it may be an upper limit, or rather a former upper limit. It may therefore represent a chilled upper portion of a laccolithic mass extending far beyond the limits of its present exposure.

It is perhaps necessary to go into this matter in greater detail, and, in order that this may be done, mention will first be made of

a much simpler example of the same phenomenon. In the Palisade diabase of New Jersey gravitative differentiation has taken place with the result that there has been formed in the lower layers an olivine-rich diabase and in the upper layers more acidic types, in local patches verging upon granite. At the upper border, however, a more basic phase occurs which contains a small amount of olivine and represents the original magma quickly chilled and undifferentiated. In this body of moderate dimensions all the differentiates have remained in position, except that the acidic phase may be injected occasionally into the more basic varieties as aplitic dikes. When this occurs, the acidic phase has been noted to exert a particularly strong corrosive or recrystallizing action on the basic phase.

While the differentiates are of other types in the case of the Adirondack complex, I believe that in a broad way the relations are substantially the same, the principal complicating circumstance being the prominence of reintrusion of the later liquid, the syenite. The gabbro border phase I believe, with Daly and Cushing, to be a chilled border, and, while this matter was not discussed in connection with the Adirondacks, mention was made of such chilled phases on page 213. In an undisturbed mass the syenite would everywhere lie immediately below this basic phase if the mass had also a very regular contact. However—and this brings us to another of Professor Cushing's objections—if the mass had an irregular upper contact, the syenite need be present only in the re-entrants of the roof and need not therefore form a continuous border about the anorthosite. Add to this the fact that the syenite has been disturbed and re-intrusion has occurred, and I think that this fact will become still more obvious. It must be confessed that Professor Cushing was perhaps justified in considering a continuous syenite body a necessary consequence of my hypothesis on account of the diagrams that were offered in illustration of the conception. But these were intended to represent in a diagrammatic way the conditions under which the various types were generated, and not to give a picture, except in a generalized way, of the actual distribution of types in the Adirondacks at present. It is recognized that reintrusion of the syenite occurred, resulting in satellitic bodies

at higher horizons in the Grenville, though much of it remained substantially where generated—enough, perhaps, to justify the statement that the Adirondack complex is "*essentially* a sheetlike mass with syenite overlying anorthosite." Whether distant syenite masses are to be regarded as related to the anorthosite I cannot say.

As a consequence of reintrusion, invasion of the anorthosite by syenite, in so far as this occurs, is especially likely to be true of the basic border phase, the anorthosite-gabbro or gabbro, and, after the manner of the acidic phases in the Palisade intrusive, it may be expected that the syenite will exert a strong corrosive or resorbing action on these basic differentiates, such as that described by Professor Cushing from Long Lake. While, therefore, the syenite would be pushed up from below into and beyond the basic phase of the anorthosite, it is considered that the syenite came into being at a higher level than the anorthosite proper. This is not inconsistent with the occasional occurrence of dikes of syenite in the anorthosite, for a splitting of the solidified anorthosite would permit the formation of such dikes from an overlying liquid syenite as readily as from a deeper-seated mass. Professor Cushing is able to bring into court more examples of these dikes than I had supposed were known, but I think that it must be admitted that in much of the quadrangle work the syenite is considered later than the anorthosite solely on the basis of his findings in the Long Lake quadrangle. This might be considered as due to failure of exposure, but in the same areas there is no lack of evidence of the invasion of the Grenville by syenite. I consider it likely, therefore, that the syenite does not invade the anorthosite in exactly the same way, but is largely transitional into it, although, being of somewhat later consolidation, it may send dikes into the anorthosite on occasion. My observations are admittedly limited, but I do not think that the intermediate types to be seen at Lake Placid are formed by interaction of the two types, an action of which Professor Cushing finds abundant evidence at Long Lake. The Placid types are quite definitely intermediate between syenite and anorthosite, not between syenite and gabbro, as are Cushing's reaction types.

In conclusion, I would state that, while Professor Cushing has raised legitimate objections and there is certainly room for difference

of opinion, it still seems to me to be advisable to keep an open mind on the possibility that the syenite and anorthosite occur "*substantially* as layers with the syenite above." It is especially desirable in view of the fact, recognized by Professor Cushing, that the anorthosite occurs in the more deeply eroded portions and the syenite principally at higher horizons, an arrangement not easily reconciled with the opinion that the syenite pushes up into the anorthosite from below.

ADIRONDACK INTRUSIVES

H. P. CUSHING

I am greatly indebted to Dr. Bowen for his additional contribution to this discussion. I take the liberty of considering briefly the points he brings out.

He suggests that the chilled gabbro border of the anorthosite is not a lateral border but a remnant of an upper one. It is very difficult for me clearly to visualize the structure of the region on this view. It is, roughly, about 100 miles across the mid-Adirondack region from east to west, and, again roughly, the easterly half of this distance is occupied by pretty clean anorthosite, and the westerly half contains a great number of syenite bodies and no anorthosite at all. The chilled gabbro border is about midway of the region. If it is a chilled upper portion of a laccolith, consisting of pyroxenite and gabbro below, then anorthosite, then syenite, and, finally, the chilled gabbro roof, since tilted so that the present erosion surface cuts it at a considerable angle, it is necessary to conceive that this chilled upper surface passes below ground in the westerly direction and into the air to the east. Under such a view the present-day syenite masses of the west must have broken through this cover to reach their present position, and there is no particular difficulty in imagining that they did so. But under this view it seems to me necessary that we should also find syenite to the east of the chilled border and close to it—that syenite which formed as a differentiate in the upper part of the chamber, underneath the chilled upper surface. Even if the upper part was very

irregular, as Bowen suggests, so that the syenite differentiate was in separate masses instead of in a continuous sheet, there should still remain considerable masses of syenite within the chilled border and underlying it, if this border was an upper instead of a lateral one. We should find gabbro passing into syenite and this into anorthosite. I know of no such syenite masses within the gabbro border anywhere in the region; and to explain their absence we should be, it seems to me, forced to the conclusion that, owing to disturbance during a late stage of consolidation, every particle of this syenite differentiate in the upper part of the body was forced out through the roof to higher levels, letting the chilled gabbro down upon the anorthosite. This is perhaps possible, but certainly very unlikely, and, moreover, it would leave unexplained the usual slow and even gradation from border gabbro into anorthosite gabbro and of this into anorthosite as we recede from the border—a feature which seems to me convincingly to suggest a lateral border rather than an upper one.

In the Palisade sheet, utilized as an illustration by Bowen, the acidic types lie directly underneath the upper chilled border. In the Adirondacks they lie without and above rather than within and below this border, as they should do on the sheet conception. None of the outlying masses of syenite known to me show any sign of a chilled border of gabbro as if they were upper parts of a single large body. They all seem rather of the type of injections upward from some large mass of magma below. It is to be understood that I am not objecting to the laccolithic conception, but to the conception of a single laccolith occupying the entire region. If we regard the anorthosite mass as a single mass, its margins shown by the chilled border, attacked shortly after its formation by masses of syenite magma, which arose from one or more separate and deeper bodies to the west and which came up along the margin of the anorthosite, not through it, we obtain an explanation of the abrupt transition from anorthosite to syenite territory which obtains in the region and we are free from the difficulties which have just been discussed.

Dr. Bowen's contention that the present-day ideas in regard to the time relationship between syenite and anorthosite are chiefly

due to my observations on the Long Lake quadrangle is correct, but needs some comment in order not to be misleading. The anorthosite district is rugged, wooded, and difficult. Very little of it has been mapped in detail on quadrangle maps. Moreover, the marginal types are weaker and less likely to be well exposed. It is as yet unsafe to argue that the Long Lake phenomena are exceptional because they have not been shown elsewhere.

I regret that Dr. Bowen did not discuss my suggested explanation of the Placid syenite inlier as a remnant of the overlying syenite differentiate of the anorthosite. It is there that he found his rocks transitional between syenite and anorthosite, and it is there that they would be expected, if the inlier is such a remnant. These rocks are not on the border, but are within the mass. If a chilled border is lacking between them and the adjacent anorthosite, then the occurrence would seem most easily explained on this theory.

In conclusion, then, the relations shown in the field along the western border of the anorthosite seem to me to indicate that the anorthosite is one body and the syenite masses to the west and south belong to one or more separate and slightly later bodies. While I welcome Dr. Bowen's theory of the formation of the anorthosite and syenite, I can neither agree with, nor see the necessity of, his idea that all these intrusives of the region are parts of one single laccolithic body. As I picture it, they must represent separate upwellings from one or more deeper-seated magmas. The western border of the anorthosite marks the line of division of the region into contrasted halves—anorthosite to the east, separate syenite masses to the west; and the particular syenite masses which happened to adjoin the anorthosite differ in no particular from those more remote, except in the one that they have assimilated some anorthosite at the contact of the two rocks. Nothing is to be gained by assuming that the adjoining masses belong with the anorthosite body and by attempting to make a separation between them and those more remote. Such a separation would be purely arbitrary, whereas the other divisional line is sharp and obvious.

A REVIEW OF THE AMORPHOUS MINERALS

AUSTIN F. ROGERS
Stanford University, California

Mineralogists generally have neglected the study of naturally occurring amorphous substances. None of the modern mineralogical textbooks or treatises give an adequate treatment of the amorphous state or condition. Crystals are treated at great length, but the amorphous state is usually given only a paragraph or two.[1]

The reasons for this neglect on the part of mineralogists are apparent. Crystals, with their great variety of form and physical properties, offer a more attractive field for study. Crystalline material so greatly predominates over amorphous material in the earth's outer shell that it is regarded as typical of the solid state. In selecting material for chemical analysis crystals are selected as far as possible, for crystallization is Nature's great method of producing pure inorganic substances.

While the mineralogist is primarily a crystallographer and while crystallography is left largely in the hands of the mineralogist, we need to be reminded that mineralogy and crystallography are by no means synonymous. Crystallography deals with crystals produced in the laboratory as well as with mineral crystals. Mineralogy deals with all homogeneous, naturally occurring, inorganic substances, whether crystalline or amorphous. The two fields overlap but do not coincide.

In view of the recent advances in colloid chemistry, the mineralogist can no longer be excused for his neglect of the study of the amorphous state. Although the science of colloid chemistry has been developed largely by chemists, Breithaupt, one of the early mineralogists and perhaps the greatest of the old natural-history

[1] Knop, however, in his *System der Anorganographie* (Leipzig, 1876), and Doelter, in his *Physikalisch-chemische Mineralogie* ((Leipzig, 1905), both treat the amorphous state at some length.

school of mineralogists, recognized colloids under the name porodine substances as early as 1817.[1] He called attention to the fundamental differences between the crystalline and amorphous conditions and divided amorphous substances into two groups: the hyaline (glasses) and porodine ("guhren" or gels). Breithaupt knew of the researches of Graham before the publication of the latter's discovery of dialysis and stated that his group of "guhren" was identical with the laboratory products of Graham.

The application of colloid chemistry to mineralogy has been pointed out by Cornu and others in a series of papers published in 1909[2], and more recently Marc and Himmelbauer[3] have contributed an excellent summary and bibliography of the whole subject.

CONFUSION OF THE TERMS AMORPHOUS AND COLLOIDAL

While the study of the amorphous condition involves a study of the colloidal or "dispersed" state, the terms amorphous and colloidal are not synonymous. Amorphous is the broader term. Ordinary glasses are amorphous but not colloidal, although some varieties of glass may be colloidal (e.g., opalescent glass). Colloids are microheterogeneous systems made up of two phases, one dispersed through another.

Most of the amorphous minerals are hardened hydrogels. The water present is usually considered to be adsorbed water. It may be adsorbed water when the colloid is first formed (even this fact is doubted by Robertson),[4] but after hardening, the water may be present in solid solution.[5] Hyalite opal, for example, is apparently a microhomogeneous substance, and there is no reason why it may not be looked upon as a true solution of water in silica. Hence it is possible, and even probable, that the mineral hydrogels are not, properly speaking, colloids, but only colloidal in origin.

[1] Cornu, *Zeit. f. Chem. u. Ind. d. Kolloide*, IV (1909), 300–4; Hunt, *Systematic Mineralogy*, New York, 1891, p. 10.

[2] *Ibid.*, IV, 15, 89, 187, 188, 189, 275, 285, 291, 295, 298, 300, 304, 306.

[3] *Fortschritte der Min., Krist., u. Petrog.*, III (1913), 11, 32.

[4] *Zeit. f. Chem. u. Ind. d. Kolloide*, III (1908), 49.

[5] The fluorin content of collophone mentioned later in this paper is an argument in favor of the solid solution theory of hydrogels.

Wolfgang Ostwald says: "The colloid solutions . . . . should always be meant when colloids in general are under discussion,"[1] and also "when we speak of a 'colloid' we nearly always mean one in this condition, in other words, one in the *sol condition*."[2]

Bütschli described the gels as possessing a honeycomb structure, but according to Bachmann[3], this is simply an optical effect. By means of the ultramicroscope the latter proved that the structure of the solid gel of silica is extraordinarily fine and for the most part amicroscopic (i.e., made up of amicrons).

Whether the hardened gels are colloidal or not, we are safe in calling them amorphous.

There is a tendency on the part of some modern mineralogists to use the term colloid, not only for the hydrogel minerals, but also for microcrystalline substances of colloidal origin. The recognition of colloidal structures in the study of minerals, rocks, and ores[4] is important, but the fundamental differences between amorphous and crystalline minerals should not be lost sight of. In the identification of minerals the mineralogist is concerned with amorphous and crystalline substances, and not primarily with colloidal structures. The confusion of the terms colloidal and amorphous is apparent in a number of recent mineralogical papers. For example, Cornu[5] classifies chrysocolla as the "gelform" of dioptase, when, as a matter of fact, chrysocolla is crystalline. Its amorphous equivalent is another mineral recognized in this paper for the first time. The use of the term *metacolloid* proposed by Wherry[6] for microcrystalline substances of colloidal origin will do much to clear up the difficulty. Cornu's term "gelform" is ambiguous, and as an illustration let us take the silica minerals. Opal is listed as the "gelform" of chalcedony by Cornu and chalcedony as a "krystalloidform." But both of the minerals have colloidal

[1] *Handbook of Colloid Chemistry* (Eng. trans. of 3d edition by Fischer, 1915), p .24.

[2] *Ibid.*, p. 40.

[3] *Zeit. f. anorg. Chemie*, LXXIII (1911), 125.

[4] For a discussion of colloidal structures in ores see Krusch, *Zeit. f. prakt. Geol.*, 21. Jahrgang (1913), 506–13.

[5] *Zeit. f. Chem. u. Ind. d. Kolloide*, IV (1909), 17.

[6] *Jour. Wash. Acad. Sci.*, IV (1914), 112.

characteristics, and if we treat them as Cornu treats chrysocolla they would both be considered as colloidal or "gelforms" of quartz. In the case of silica minerals, for example, ambiguity is avoided if we call opal amorphous silica and chalcedony metacolloidal silica.[1]

CRITERIA FOR THE RECOGNITION OF AMORPHOUS SUBSTANCES

To the mineralogist is committed the task of describing and defining all of the definite, homogeneous, naturally occurring substances, whether they be crystalline or amorphous.

How may amorphous substances be distinguished from crystalline substances? On the face of it this seems to be easy, but, as a matter of fact, the problem is often very difficult. Crystalline substances may be defined as those having discontinuous vectorial properties[2] and amorphous substances as those not having such properties, but the actual determination of whether a given substance has discontinuous vectorial properties or not may be very difficult.

From the standpoint of physical chemistry amorphous solids are liquids. Now, the shape of a liquid unaffected by gravity or other external influence is spherical, and so we often find the hydrogel minerals in spherical, botryoidal, reniform, stalactitic, and mammillary forms. These forms intergrade, so that one is often at a loss to know which term to use. I therefore propose the term *colloform* for the rounded, more or less spherical, forms assumed by colloidal and metacolloidal substances in open spaces. Some crystalline, not merely microcrystalline, minerals, such as smithsonite, also occur in colloform crusts, and it should be emphasized that this term refers only to the shape or form, and not to the condition of the material.

Colloform minerals may be either amorphous or crystalline, while, on the other hand, minerals occurring in euhedral crystals may be amorphous alteration products of original crystals, for example, malacon, which is a pseudomorph after zircon. Yttrotantalite, thorite, allanite, gadolinite, homilite, and yttrocrasite all occur in euhedral tetragonal, orthorhombic, or monoclinic crystals.

[1] Chalcedony may be either a distinct mineral or a variety of quartz.

[2] Friedel, *Leçons de Cristallographie* (Paris, 1911), p. 2.

Yet in many cases the material is optically isotropic and we apparently have the amorphous equivalents of these minerals occurring as pseudomorphs after the original crystalline minerals. The typical structures of crystalline aggregates, such as fibrous, lamellar, etc., do not necessarily indicate crystallinity, for these structures may be remnants of an original crystalline condition, now consisting of amorphous material. Pyrolusite, for example, is probably an amorphous manganese dioxid produced by the dehydration of crystalline manganite, which accounts for its fibrous structure.

In the absence of cleavage and other direct proofs of crystallinity we must rely largely upon optical tests for transparent and translucent minerals. A serious difficulty confronts us here, for isometric crystals, as well as amorphous solids, are optically isotropic, and anhedral isometric crystals without cleavage may be confused with amorphous substances of similar appearance.

Still another difficulty lies in the fact that many amorphous substances are doubly refracting. This is especially true of colloform crusts, and the double refraction here is due to strains set up in the hardening of the gel. The hyalite variety of opal practically always shows double refraction. The birefringence of an amorphous mineral is usually very weak, but in some cases it reaches an appreciable amount. In a specimen of phosphorite from Lassa Island containing both dahllite and collophane the double refraction of colloform bands of amorphous collophane is greater than that of the corresponding crystalline dahllite. Double refraction due to strain can usually be distinguished from the double refraction of optically anisotropic crystalline substances by its lack of uniformity.

For opaque minerals etching experiments are perhaps the most satisfactory tests to try in the absence of evident crystalline structure. Tolman[1] has recently described metacolloidal chalcocite. The determination was made by examining polished surfaces etched by nitric acid with the metallographic microscope.

From the foregoing discussion it is evident that in many cases the scalar properties must be used to distinguish amorphous and crystalline substances, and it should be emphasized that the optical properties are also scalar for isometric crystals.

[1] *Bull. 110 Am. Inst. Min. Eng.*, 1916, p. 410.

Among the scalar properties are specific gravity, specific heat, fusibility, solubility, and also the index of refraction for both isometric crystals and amorphous substances. Now, any one of these properties is somewhat different[1] for an amorphous substance and the corresponding crystalline substance, i.e., one with the same, or approximately the same, chemical composition. The solubility and fusibility are not easy to determine accurately, and this is often true of the specific gravity.

The determination of the index of refraction, and not the presence or absence of double refraction, furnishes the most generally available means of identifying a given amorphous mineral. Irregular grains of garnet in the form of sand, for example, are identified as garnet, not because it proves to be crystalline, but because of the isotropic character, high index of refraction, absence of cleavage, pink color, etc. We know it to be crystalline simply because it is garnet. An amorphous mineral corresponding to garnet would have a lower index of refraction. It might be difficult to prove that such a mineral is amorphous in the first place, but if this fact were once established the mineral could be distinguished from garnet or, more accurately speaking, from one of the members of the garnet group by its index of refraction. The index of refraction, however, is sometimes misleading. For example, lussatete is a fibrous variety of silica probably identical with chalcedony, yet it has the index of refraction of opal. The explanation is that minute fibrous aggregates of chalcedony have gradually crystallized out of an amorphous mass of opal.

Many of the amorphous minerals may be distinguished from their crystalline equivalents by the presence of water, which seems to be almost universally present in the amorphous minerals.

THE GENERALLY RECOGNIZED AMORPHOUS MINERALS

Comparatively few amorphous minerals are recognized in standard works on mineralogy. In Dana's *System of Mineralogy* (6th edition, 1892) with its three appendixes (1904, 1909, 1915), for example, approximately one thousand minerals are given the rank

[1] See Knop, *op. cit.*, p. 8.

of distinct species, and of these only seventeen[1] are listed as amorphous. Some of these are probably synonyms and some are undoubtedly crystalline. Of the amorphous minerals described since the appearance of Dana's *System* none has been given the rank of mineral species in the appendixes of that work.

The principal reason why so few amorphous minerals are listed is because the amorphous equivalents of crystalline minerals, with the single exception of opal, are not recognized as distinct mineral species. We find, for example, crystalline cupric oxid (tenorite) united with amorphous cupric oxid (melaconite). Amorphous limonite is united with its fibrous and crystalline equivalent. Crystalline and amorphous ferric oxid are both included under the name hematite.

ARE AMORPHOUS MINERALS TO BE RECOGNIZED?

The chemical composition of most amorphous minerals is not as definite as that of the average crystalline mineral, but since the discovery of the variability in the composition due to solid solution of such well-crystallized minerals as pyrrhotite and nephelite, we can no longer insist that the term "mineral species" be confined to those of definite chemical composition. Many of the amorphous minerals approach closely in chemical composition the corresponding crystalline mineral, as was first emphasized by Cornu,[2] who called these minerals "pseudo-stöchiolithe." Practically all the amorphous minerals contain water, even if the corresponding crystalline minerals are anhydrous, but this water or the excess water over that present as hydrion or hydroxyl is probably not essential. The myeline from Rochlitz, Saxony, for example, is probably the amorphous equivalent of kaolinite, yet it contains practically the same amount of water.

Some of the amorphous minerals are definite enough to be recognized, though we must, of course, allow more latitude in

[1] These are opal, collophanite, bindheimite, szmikite, deweylite, genthite, garnierite, spadaite, saponite, glauconite, cimolite, montmorillonite, allophane, collyrite, schrötterite, chloropal, and hisingerite.

[2] *Zeit. f. Chem. u. Ind. d. Kolloide,* IV (1909), 15, 89.

chemical composition and physical properties than with crystalline minerals. The physical properties of many of the amorphous minerals can be determined as completely as those of many of the massive non-cleavable isometric minerals, for in the absence of cleavage and crystal form all the available properties for determination are scalar.

Most authorities admit an amorphous mineral to the full rank of species if it has no crystalline equivalent, but discard those with crystalline equivalents. This, I believe, is inconsistent, and it would seem more logical to refuse admittance to an amorphous mineral until its crystalline modification is described. It is also inconsistent to recognize opal and not the other amorphous equivalent of crystallized minerals. Opal is not a definite hydrate of silica, but is silica with dissolved or adsorbed water. Other amorphous minerals also contain dissolved or adsorbed water and bear the same relation to crystalline equivalents that opal does to quartz. As shown by von Weimarn,[1] the colloidal condition is a general property of matter. No one can doubt that the amorphous and crystalline conditions are fundamentally different. Any given substance possesses a different energy content in these two conditions.

If it is admitted that the properties of amorphous minerals are sufficiently distinct, and we admit this when we use such names as opal, pitticite, allophane, etc., we must assign the known amorphous equivalents of crystallized minerals the rank of independent mineral species. The first step in this direction was taken, I believe, by Cornu[2] in 1909. He introduces the names kliachite, stilpnosiderite, gelvariscite, gelfischerite, geldiadochite, gelpyrophyllite, etc., as names of the amorphous equivalents of hydrargillite, limonite, variscite, fischerite, diadochite, and pyrophyllite, respectively. This, in my opinion, is one of the important advances in systematic mineralogy. Although sound from the standpoint of physical chemistry, this principle has not been generally adopted. We are conservative, and even desirable changes are slow in adoption, but it seems strange that such names as cliachite or kliachite are not

[1] *Zur Lehre von den Züstanden der Materie* (Leipzig, 1914).

[2] *Zeit. f. Chem. u. Ind. d. Kolloide*, IV (1909), 15.

adopted when so many new names of mere varieties or mixtures of older minerals[1] are apparently welcomed.

NAMES FOR AMORPHOUS MINERALS

If it be granted that amorphous minerals deserve recognition, then names of some kind are necessary. Are these to be distinctive names or modifications of the names of the corresponding crystalline minerals? Cornu used the prefix "gel" with the crystalline modification (e.g., gelvariscite, for the amorphous equivalent of variscite). Tućan[2] employed a similar device, except that "gel" came after the root name instead of before it (e.g., hematogelite for colloidal ferric oxid). Wherry[3] proposed that the Greek letter κ (the abbreviation of $\kappa o\lambda\lambda\alpha$) be used as a prefix to the crystalline compound (e.g., κ-limonite for stilpnosiderite).

A serious objection to all these proposals lies in the fact that the amorphous mineral is not related to one polymorphous modification any more than to another. Most mineral substances are known in but one crystalline modification, but other modifications may be found in the future, as polymorphism seems to be a general phenomenon of nature.

The name of any crystalline mineral connotes certain crystal forms and physical properties as well as a given chemical composition. It is absurd, then, to speak of amorphous calcite or amorphous aragonite. The proper term to use is amorphous calcium carbonate.

Distinctive names, then, are necessary, or at least advisable, for the amorphous equivalents of crystalline as well as for the other amorphous minerals. As an illustration of the need of distinctive names for amorphous minerals, let me cite the case of variscite. Cornu, in 1909, called its amorphous equivalent gelvariscite, but Schaller has recently described lucinite, a dimorph of variscite.

Few new names are necessary, for varietal and other discarded names may be used. In this paper I have recognized about twenty

[1] See paper by the author, "The Nomenclature of Minerals," *Trans. Am. Phil. Soc.*, LII (1913), 606–15.

[2] *Centralblatt f. Min. Geol. u. Pal.*, 1913, p. 68.

[3] *Ibid.*, pp. 517–18.

of the best-defined amorphous minerals and have found it necessary to introduce but two new names. In the future other new names will be necessary, but their introduction will be gradual. It is not desirable to recognize all amorphous mineral substances, but only those that will stand the test of a critical examination, and usually only those that are found in a number of localities. I would emphasize especially the recognition of those with crystalline equivalents, for then we have a comparison of properties which are especially useful in determination.

SOME OF THE PROMINENT AMORPHOUS MINERALS

I now propose to describe and discuss what seem to be the better established amorphous minerals, with especial emphasis upon those that I have been able to study in more or less detail.

Amorphous carbon (schungite, mineral charcoal).—Graphite is the hexagonal modification of carbon, and the so-called amorphous graphite is probably compact, dense graphite in a fine state of division. Graphitite and graphitoid, according to Weinschenk,[1] are simply varieties of graphite.

Schungite, described by Iostranzeff from near Schunga, Government Olenez, Russia, is an amorphous modification of carbon, for when treated with a mixture of potassium chlorate and nitric acid it is soluble and is not, like graphite, converted into the yellow, scaly substance called graphitic acid.

Amorphous sulfur (sulfurite).—Besides the common orthorhombic, and the rare monoclinic, sulfur found at a few localities amorphous sulfur also probably occurs in nature. Rinne[2] has proposed the name sulfurite for naturally occurring amorphous sulfur. He describes an arsenical variety (arsensulfurite) which occurs as amorphous crusts on andesite.

Xanthochroite $CdS(H_2O)_x$? (greenockite in part).—The cadmium sulfid which occurs as a thin incrustation on sphalerite is amorphous, as has been recognized by Lacroix and by Christomanos. It is usually called greenockite, but the original cadmium sulfid first described from Scotland and found in but few other

[1] *Zeit. f. Kryst. u. Min.*, XXVIII (1897), 291.

[2] *Centralblatt f. Min. Geol. u. Pal.*, 1902, p. 499.

localities is hexagonal. A new name is necessary for amorphous cadmium sulfid and I propose to call it *xanthochroite* (Greek *xanthos*, yellow, *chroa*, color).

This mineral has recently been found. near Topaz, Mono County, California, where it occurs as a thin coating on massive magnetite. With the magnetite is associated sphalerite, and the xanthochroite is doubtless a secondary mineral derived from sphalerite. It varies from yellow to orange in color and is almost opaque when examined with the microscope. There is no evidence of crystallization or double refraction. It is soluble in hydrochloric acid and is reprecipitated by hydrogen sulfid. It is immediately darkened by copper sulfate solution, and this will probably distinguish it from crystalline greenockite.

Hydrotroilite. $FeS(H_2O)_x$.—The black slime found in inland seas and in some moist sands and clays is colloidal and amorphous ferrous sulfid. It has been described from Hadishibey Liman in Southern Russia by Sidorenko[1] and the name hydrotroilite given to it. As troilite is a synonym of pyrrhotite, the name is not a very fortunate one, but it has priority.

I am indebted to Mr. G. A. Waring, of the United States Geological Survey, for a black slimy deposit from the Kruzgekampa Spring, 60 miles north of Nome, Alaska. This consists of a black, opaque substance mixed with sand grains and diatoms. The black substance is hydrotroilite. It is soluble in cold hydrochloric acid with the evolution of hydrogen sulfid. The solution gives tests for ferrous iron, and with ammonia a black precipitate is obtained.

Wherry[2] proposes to call the melnikowite of Doss[3] κ-pyrite, but melnikowite is microcrystalline (metacolloidal) FeS_2 and not amorphous. This is a serious objection to Wherry's scheme of nomenclature.

Opal. $SiO_2(H_2O)_x$ (lardite).—Opal is a typical amorphous hydrogel and is unique in that, until Cornu's work in 1909, it was the only amorphous equivalent of a crystallized mineral generally

[1] For reference to original article see *Neues Jahrb. f. Min. Geol. u. Pal.*, II (1902), ref. p. 397.

[2] *Central. f. Min. Geol. u. Pal.*, 1913, p. 518.

[3] *Neues Jahrb.*, Beil. Bd. XXXIII (1912), 689–93.

recognized as a distinct species. The properties of opal are so well known that a description is unnecessary. Attention, however, should be called to the fact that hyalite opal, the purest and most typical form of opal, usually shows double refraction due to strain.

(*Lechateliérite*) ?—The amorphous constituent of fulgurites and of some inclusions in volcanic rocks has recently been named lechateliérite by Lacroix.[1] This material approaches silica glass in composition and is also very similar to opal in properties. The only difference between lechateliérite and opal is due to their previous history, but, as Miers says, ". . . . the essential character of a mineral, moreover, is quite independent of its source or previous history."[2] Yet these two substances are so different in occurrence and origin that one feels inclined to consider them as distinctive minerals. Then we are confronted with the question whether we are ever to recognize more than one amorphous mineral for a given crystalline equivalent or not.

Now, lechateliérite is a glass and may be considered along with other natural glasses as a mineraloid (see p. 540) rather than as a mineral proper. As an argument for this, I give the results of my examination of a fulgurite found in the sand dunes along Lake Michigan in Van Buren County, Michigan, and obtained from Ward's Natural Science Establishment. The fulgurite is a hollow tube of glass with small grains of white sand adhering to the exterior surface. The sand grains are quartz and orthoclase. The glass is colorless and perfectly isotropic with an index of refraction of 1.462 ± 0.003. It is fusible on the edges and gives a small amount of water in the closed tube. From these tests it can be seen that the glass is not pure silica, but a glass high in silica. The lechateliérite described by Lacroix is almost pure silica, as its index of refraction is 1.458. Whether a distinctive name is desirable or not, the glass of fulgurites may be considered simply as a mineraloid, which approaches pure silica glass in composition.

Hydrocuprite. $Cu_2O(H_2O)_x$ (hydrocuprite, ziegelite, ziguéline, tile-ore).—Two kinds of cuprous oxid occur in nature: (1) isometric cuprite and (2) amorphous tile-ore, for which the name

[1] *Bull. Soc. Fran. de Min.*, XXXVIII (1915), 182–86.

[2] *Mineralogy*, 1902, p. v.

hydrocuprite may be used. Werner considered *rothkupfererz* and *zeigelerz* as co-ordinate. Beudant used the name ziguéline as a species name for cuprous oxid. Hydrocuprite was described by Genth[1] as an orange-yellow to orange-red, amorphous raglike coating on magnetite from Cornwall. The same substance has been noted by Lacroix on cuprite from Chessy, France, and by Sandberger, mixed with cuprite, from Schapbach, Baden. According to Schaller[2] the supposed vanadium ocher from Lake Superior is hydrocuprite (or possibly cuprite).

I have observed what I consider to be amorphous cuprous oxid in specimens from the Lowell mine, Bisbee, Arizona; the Poderosa mine, Collahuasi, Chile; and an unknown locality. The hydrocuprite occurs as a massive brick-red mineral associated with cuprite. Under the microscope it appears as an orange-colored, almost opaque substance in contrast to the dark-red translucent cuprite. No very satisfactory optical tests can be made on account of the opacity, but in a few spots the orange-colored mineral is isotropic as well as the cuprite.

On account of the optically isotropic character of both of these minerals the closed-tube test may prove useful. Hydrocuprite contains water, but it is not a definite hydrate, as the name implies.

Melaconite. $CuO(H_2O)_x$ (tenorite in part, melanochalcite).—Dana united the crystalline tenorite and amorphous melaconite under the name tenorite, but they should be separated. Crystalline tenorite is a very rare mineral, known only from Vesuvius, Cornwall, and Keweenaw Point, Michigan, but the amorphous melaconite is a fairly common mineral in the oxidized zone of copper mines. It is a black, massive mineral and occasionally occurs in colloform crusts. In fragments it is black and opaque, but is usually translucent brown and isotropic on the thin edges. In addition to cupric oxid and water melaconite also contains silica, the carbonate radical, and often manganese oxid.

Melanochalcite, described by Koenig as a copper salt of silicocarbonic acid, is undoubtedly melaconite. Kraus and Hunt[3]

[1] *Preliminary Report on the Mineralogy of Pennsylvania*, Pennsylvania Second Geol. Surv., 1875, p. 46.

[2] *Am. Jour. Sci.* (4), XXXIX (1915), 404.

[3] *Ibid.*, (4), XLI (1915), 211–14.

decide that melanochalcite is a mechanical mixture of tenorite, malachite, and chrysocolla. While the two latter minerals may sometimes be associated with it, homogeneous melaconite free from mechanical impurities also gives tests for the carbonate radical and silica. Melaconite is either an adsorption compound or a solid solution of cupric oxid and water with silica, carbonate radical, and often manganese dioxid.

Hematite. $Fe_2O_3(H_2O)_x$ (hydrohematite, turgite, hematogelite).—Two varieties of ferric oxid are generally recognized, a crystalline one and a massive or earthy-red one. Haüy and Werner respectively considered these as distinct minerals under the names fer oligiste, fer oxydé rouge and eisenglanz, rotheisenstein. They were united by Hausmann, and he has been generally followed by other mineralogists. The red, earthy varieties of ferric oxid, such as the oölitic Clinton ore and the soft hematites from the Mesabi range, are amorphous and should be separated from the crystalline ferric oxid. The amorphous ferric oxid may be distinguished from the crystalline mineral by the fact that it contains a small amount of water.

Turgite is usually considered to be $2Fe_2O_3 \cdot H_2O$, but it is probably not a definite hydrate. Turgite often occurs in colloform crusts. It sometimes shows a fibrous structure, but this is probably because it is a dehydration product of limonite and retains its structure. In fragments turgite is very dark red, sometimes isotropic and sometimes birefringent. The double refraction may be due to strain. Turgite is essentially identical with amorphous hematite.

Specularite, now used as a varietal name by many mining geologists, may be used as a specific name for crystalline ferric oxid, and hematite then may be used exclusively for amorphous ferric oxid.

Limonite. $Fe_4H_6O_9(H_2O)_x$(?) (stilpnosiderite, melanosiderite, limnite, esmeraldaite, xanthosiderite ?).—Leaving göthite out of consideration, hydrous ferric oxid with a yellow-brown streak occurs in two distinct forms, a crystalline fibrous form and an amorphous massive form. Under the microscope the former appears as crystalline fibers with parallel extinction, and the latter is

optically isotropic and usually structureless. As Cornu suggests, these two forms should have distinctive names. He used limonite for the crystalline mineral and stilpnosiderite for the amorphous one, but in view of the fact that the simpler name limonite is so well established for the common and widely distributed brown hydrated iron ore of surface origin it seems advisable to retain the name limonite for the amorphous mineral. Limonite in this restricted sense has priority over stilpnosiderite, for it was used by Hausmann in 1813, while the name stilpnosiderite was introduced by Ullmann in 1814 and usually has been used as a varietal name for *eisenpecherz.*

A new name is necessary for the crystalline mineral with the composition $Fe_4H_6O_9$, but in view of the fact that the mineral hydroxids of irod are being investigated by the Geophysical Laboratory no suggestion is offered at present.

The melanosiderite of Genth is not an iron silicate, but limonite with dissolved or adsorbed silica. The water content of the amorphous ferric oxids is variable, and so it is probable that xanthosiderite, limnite, and esmeraldaite are not definite hydrates, but are all simply varieties of limonite.

Stibiconite. $Sb_2O_4(H_2O)_x$ (stibianite, stiblith, stibioferrite, volgerite).—The most common alteration product of stibnite is the amorphous mineral stibiconite. It is probably colloidal antimony tetroxid with adsorbed or dissolved water and not a definite hydrate. The existence of crystalline antimony tetroxid is doubtful, for no accurate description of cervantite has ever been made. Tenné and Calderon state that much of the supposed Spanish cervantite is valentinite.

Cliachite. $Al_2O_3(H_2O)_x$ (bauxite in part, wocheinite, sporogelite, alumogel, shanyavskite).—Bauxite should be used as the name of a certain type of rock and not as a mineralogical term. It was so regarded by Dufrenoy, who introduced the name in 1845. He has been followed by Tućan, Tschermak, and Lacroix. Dittler and Doelter, however, use bauxitite for the rock name.

The principal constituent of bauxite is an amorphous mineral called cliachite (kliachite) by Cornu, who revived the name used by Breithaupt.

The crystalline mineral corresponding to cliachite is hydrargillite or gibbsite. This occurs to a minor extent in pisolitic bauxite and also in some clays, but in the "granitic type" of bauxite from central Arkansas[1] hydrargillite is the principal mineral.

The composition of bauxite is usually given as $Al_2O_3 \cdot 2H_2O$, but, as in the other amorphous minerals, the water content of cliachite is variable. In the purest of the Georgia bauxites the ratio of Al_2O_3 to H_2O is very close to 1 to 3, according to Watson.[2]

An amorphous mineral from India described by Warth[3] under the name gibbsite has the composition $Al_2O_3 \cdot 3H_2O$ and is probably cliachite.

Shanyavskite, an amorphous mineral with the composition $Al_2O_3 \cdot 4H_2O$, is probably essentially the same as cliachite.

I have examined several specimens of cliachite and have found the index of refraction to be 1.570 ± 0.005.

Pyrolusite. $MnO_2(H_2O)_x$.—Pyrolusite is probably an amorphous manganese dioxid corresponding to crystalline polianite. The fibrous structure is due to the fact that it is pseudomorphous after manganite. It always contains a small amount of water.

Psilomelane. Formula doubtful (wad, lithiophorite, asbolane, lampadite).—Lacroix says that psilomelane is crystalline. There may be crystalline equivalents of psilomelane, such as hollandite and romanéchite, but most specimens of psilomelane show no indication of crystalline structure and are doubtless amorphous. Psilomelane is probably a salt of some manganese acid and not simply an oxid of manganese. Along with water it may contain BaO, CaO, MgO, Fe_2O_3, Al_2O_3, K_2O, Na_2O, Li_2O, CoO, and CuO. A specimen from near Sodaville, Nevada, presented to me by Mr. L. B. Spencer, is said to contain SnO_2 and WO_3.

Collophane. $3Ca_3(PO_4)_2 \cdot Ca(CO_3,F_2)(H_2O)_x$ (apatite in part, collophanite, fluocollophanite, quercyite, nauruite).—The principal constituent of phosphorite or so-called phosphate rock is not massive apatite, but an amorphous substance which is identical with

[1] Mead, *Econ. Geol.*, X (1915), 41.

[2] *Am. Geol.*, XXVIII (1901), 25.

[3] *Mineral. Mag.*, XIII (1902), 172.

the kollophan of Sandberger. Collophane[1] is a calcium carbono-phosphate approaching the formula given above. When the mineral was first described, the calcium carbonate present was thought to be an impurity and so was deducted from the analysis. The chemical composition, as with most amorphous minerals, is variable and somewhat uncertain, because it is difficult to distinguish mechanical impurities from essential constituents.

Fluorin is present in some specimens, and Lacroix uses the name fluocolophanite for varieties rich in fluorin. Artini[2] describes an amorphous mineral in the phosphorites of Es Salt, Palestine, which he says is a fluorcollophanite near fluorapatite in composition. I have found that fossil bones consist of the mineral collophane, and Carnot[3] has shown that the fluorin content of fossil bones increases with the geological age of the bones. If there is an amorphous equivalent of fluorapatite, should a distinctive name, such as fluocollophane, be used for it? As more latitude must be allowed in the chemical composition of amorphous minerals than in the crystalline minerals, it hardly seems advisable to use more than one name (collophane) for amorphous equivalents of minerals of the apatite group. The fluorin determination is not an accurate one, and fluorin in analyses of the phosphorites may be due to fluorite or residual apatite.

Collophane is a massive mineral and often has oölitic or concretionary structure. In cavities it appears in colloform crusts and often resembles opal. The color is sometimes white, but is usually yellow, brown, or black, and is probably due to an organic pigment.

Collophane is isotropic in part, but frequently shows double refraction. In a specimen of phosphorite from Lassa Island the double refraction of the colloform collophane is greater than that of the accompanying fibrous dahllite. I have examined specimens

[1] Dana changed kollophan to collophanite, but since the name has not come into general use it is preferable to use the English equivalent of the original, which is a simpler and more euphonious name. Another argument is that collophanite may be confused with colophonite, a variety of garnet.

[2] Abstract in *Zeit. f. Kryst. u. Min.*, LV (1915), 320.

[3] *Ann. de Mines* (9), III (1893), 155.

of fossilized bones consisting of collophane which shows an appreciable amount of double refraction. The double refraction is variable from spot to spot, and the result is a characteristic wavy extinction.

In view of these facts the safest method of distinguishing collophane from dahllite is usually by means of the index of refraction. I have determined the index of refraction of collophane from many localities and have found that it usually varies from 1.57 to about 1.61,[1] while that of dahllite varies from about 1.61 to 1.63. With high magnification dahllite shows a fabrous structure which is lacking in collophane.

Like dahllite, collophane is soluble in hot nitric acid with effervescence, but in the closed tube it gives a great deal of water while dahllite gives little or none.

The quercyite of Lacroiz[2] is collophane and not a mixture of dahllite and collophane. I have examined a specimen of a banded calcium carbonophosphate mineral labeled "Hydroapatite, Marseilles, France," which is identical with Lacroix's quercyite. The doubly refracting layers of my specimen and probably of the specimens figured by Lacroix (*op. cit.*, p. 580) are collophane and not dahllite. In support of this view it may be mentioned that the index of refraction (1.598 ± 0.002 in my specimen, but Lacroix gives 1.608) is too low and the water content (3.2 to 6.0 per cent) too high for dahllite. Double refraction is by no means a proof of crystallinity. Lacroix also mentions the fact that the fibers of quercyite lack the individuality of those of dahllite (and staffelite), which is a good argument in favor of its being collophane.

Monite from Mona Island in the West Indies is also a variety of collophane. It is a white, earthy, massive mineral which, under the microscope, is largely isotropic with small doubly refracting spots. The index of refraction is 1.631 ± 0.001, a little higher than for most specimens of collophane. Monite effervesces vigorously in hot nitric acid, so that the carbonate radical was overlooked in Shepard's analysis. In the closed tube it gives abundant

[1] The fluorcollophanite described by Artini (*loc. cit.*) has an index of refraction of 1.630.

[2] *Mineralogie de la France*, IV (1910), 579.

water. Monite also contains the sulfate radical, but this is not present as gypsum, as Shepard thought, for the mineral is homogeneous except for minute crystals of monetite and colloform crusts of dahllite. The sulfate radical probably replaces part of the carbonate radical. Phosphorites from Idaho and South Carolina also contain the sulfate radical.

Nauruite described by Elschner[1] from the island of Nauru is another synonym of collophane. It is a yellow to brown resinous mineral occurring as agate-like layers in cavities of phosphorite. The formula given is $3Ca_3P_2O_8 - \left\{ \begin{matrix} Ca(OH)_2 \\ CaF_2 \end{matrix} \right\}$. The analyses of the Nauru phosphorites all show calcium carbonate, and specimens of typical nauruite kindly furnished by Mr. Elschner effervesce vigorously in hot nitric acid. Under the microscope the Nauru collophane shows banded spherulitic structure and weak double refraction. The index of refraction is 1.597 ± 0.001, which proves that the mineral is not dahllite in spite of its birefringence. The double refraction is variable and is lost upon heating.

I have examined thin sections of phosphorites or so-called phosphate rocks from Florida, South Carolina, Tennessee, Kentucky, Idaho, Nauru, Fanning Island, Ocean Island, Lassa Island, and Clarendon, New Zealand, and have found amorphous collophane to be the principal constituent of all of them. It is often accompanied by dahllite. It seems strange that so little attention has been paid to these carbonophosphate minerals, for they are important from both the economic and scientific standpoints.

Evansite. $Al_3(OH)_6PO_4 \cdot (H_2O)_x$?—Evansite, a hydrous aluminum phosphate described by Forbes in 1864, is a typical amorphous mineral. It occurs as a colloform incrustation and greatly resembles allophane. The index of refraction determined on a specimen from Zelegnik, Hungary, is 1.483 ± 0.003.

Evansite has recently been described from two American localities (Goldburg, Idaho, and Columbiana, Alabama) by Schaller.[2]

Pitticite. $FeAsO_4 \cdot Fe_2O_3 \cdot (H_2O)_x$?—Pitticite is a dark-brown massive mineral resembling limonite. It is a basic ferric aresenate

[1] *Corallogene Phosphat-Inseln Austral Oceanien und Ihre Produkte* (Lübeck, 1913), p. 54.

[2] *Bull. 490, U.S. Geol. Surv.*, 1911, p. 94.

and often contains the sulfate radical. An artificial colloidal basic ferric arsenate has been described by Holmes and Rundfusz.[1]

I have examined specimens of pitticite from two localities, one on the west side of the South Merced River in Mariposa County, California, and the other at Sioux City, Iowa. At the first locality it is an oxidation product of arsenopyrite and at the second it occurs with limonite and aragonite.

Pitchblende $UO_2,UO_3,(H_2O)_x$ (Uraninite in part, nasturan).—The colloform or massive pitchblende seems to be the amorphous equivalent of isometric uraninite. Its water content is higher and its nitrogen and rare earth content lower than that of uraninite. It may also be distinguished by its lower specific gravity (6.5 to 8; uraninite is 9 or above).

Uraninite occurs in pegmatites while pitchblende occurs in metalliferous veins with sulfids.

(*Maskelynite*) ?—Maskelynite was first described by Tschermak from the Shergotty (India) meteorite. It is optically isotropic and in composition is very close to a plagioclase with equal molecular percentages of albite and anorthite. As the index of refraction is almost exactly the same as that of an artificial glass[2] of the composition Ab_1An_1, it is probably the amorphous equivalent of plagioclase (not necessarily a fused plagioclase) and not an isometric mineral.

Maskelynite is on the same footing as lechateliérite. They are the only glasses which have been regarded as minerals within recent years. They may be disposed of by considering them mineraloids rather than as definite minerals.

Malacon. $ZrSiO_4(H_2O)_x$? (cyrtolite, auerbachite, oerstedite, ostranite).—Malacon is the name given to a mineral from Hitterö, Norway, which has the form of zircon, but is softer and contains water. It is undoubtedly an alteration product and in all probability the amorphous equivalent of zircon. It deserves recognition as a distinct mineral, and Lacroix so regards it.

Malacon may be distinguished from zircon, not only by its isotropic character and water content, but also by its inferior hardness and specific gravity and its lower index refraction ($n=1.826$

[1] *Jour. Am. Chem. Soc.*, XXXVIII (October, 1916), 1970.

[2] Larsen, *Am. Jour. Sci.* (4), XXVIII (1909), 267.

Larsen). The other minerals mentioned above (cyrtolite, etc.) are probably synonyms of malacon.

Halloysite. $H_4Al_2Si_2O_9(H_2O)_x$ (myeline, indianaite, clayite, bole in part, kaolin in part).—It is generally recognized that some of the clays consist in whole or in part of amorphous aluminum silicates. Mellor[1] has proposed the name clayite for the amorphous constituent, but fortunately halloysite has priority.

Halloysite may be regarded as the amorphous equivalent of crystalline kaolinite, for it has the formula $H_4Al_2Si_2O_9 + _x(H_2O.)$ In LeChatelier's experiments on halloysite the water given off below 250° C. varied within wide limits, while the water given off above this temperature was fairly constant and corresponded to that of kaolinite.

Myeline is an indurated clay from Rochlitz, Saxony, which is almost identical with kaolinite in chemical composition. I have examined a specimen from the type locality and find it to be essentially amorphous (there are patches of micro-crystalline material) with an index of refraction of 1.556 ± 0.001. Gagel[2] has described a non-crystalline myeline-like substance which occurs as an alteration product of trachydolerite at Canical, Madeira.

I have examined indianaite from St. Lawrence County, Indiana, which the published analyses show is a very pure halloysite, and find it to be an amorphous mineral with an index of refraction of 1.538 ± 0.002, which is less than that of kaolinite ($n = 1.567 - 1.561$).

A clay from Morton, Minnesota, with imperfect pisolitic structure consists largely of an amorphous substance with an index of refraction of 1.557 ± 0.003, and hence may be referred to halloysite. This clay also contains some hydrargillite.

I have examined "kaolin" from Broken Hill, New South Wales, and find it to be amorphous with $n = 1.548 \pm 0.002$. This must be halloysite.

The "isotropic kaolinite-like mineral" described by Larsen and Wells[3] from Wagon Wheel Gap, Colorado, has an index of refraction

[1] *Trans. Eng. Cer. Soc.*, VIII (1908).

[2] *Central. f. Min., Geol., u. Pal.*, 1910, p. 225.

[3] *Proc. Nat. Acad. Sci.*, II (1916), 364.

of 1.557 and a water content of 15.5 per cent, and hence should be referrred to halloysite.

Helmhacker[1] describes halloysite with a small botryoidal surface from Banat, Hungary. The Rochlitz myeline also shows colloform crusts in cavities.

From the available evidence it seems clear that halloysite is the amorphous equivalent of kaolinite. The recognition of this may help in a clearer understanding of the constitution of clays. The determination of the index refraction, which varies from 1.538 to 1.557, is probably a safer means of distinguishing halloysite from kaolinite than the absence of double refraction. The presence of aluminum hydrate in solid solution may, however, modify the index of refraction.

Allophane. $Al_2SiO_5(H_2O)_x$ (carolathine).—Allophane has long been recognized as one of the typical amorphous minerals. Its colloform shape, optical isotropism, and absence of cleavage and structure leave no doubt as to its amorphous character. The index of refraction of a specimen from Bedford, Indiana, is 1.473 ± 0.003.

Whether schrötterite and collyrite should be considered synonyms of allophane is open to question.

Stevensite. $H_2Mg_3(SiO_3)_4 \cdot (H_2O)_x$ (talc in part, lucianite?).—An alteration product of pectolite found at several localities in New Jersey is probably the amorphous equivalent of crystalline talc. This substance was first described by Leeds[2] who used stevensite as a name for talc pseudomorphous after pectolite. Glenn[3] has recently studied this mineral, and his work proves that it should be considered a distinct mineral. Wherry made a microscopic examination and shows that it is isotropic with an index of refraction of about 1.50. Stevensite is also distinguished from talc by its lower specific gravity and higher water content.

Stevensite is probably not a monohydrate of talc, as Glenn suggests, but the water content is evidently variable and reaches over 19 per cent in the clay mentioned in the next paragraph.

[1] *Min. u. petr. Mitth.*, II (1879), 232.

[2] *Am. Jour. Sci.* (3), VI (1873), 22–23.

[3] *American Mineralogist*, I (1916), 44–46.

Hilgard[1] has recently described, from a locality near the City of Mexico, a peculiar clay which consists largely of a hydrous magnesium silicate. This substance was named lucianite, but as it is a colloidal substance with specific gravity of 2.25 and is soluble in hydrochloric acid it is probably a synonym of stevensite.

Cornuite. $m\mathrm{CuO} \cdot n\mathrm{SiO_2} \cdot (\mathrm{H_2O})_x$ (chrysocolla in part).—In specimens of chrysocolla from a number of localities I have noted a glassy, green or bluish-green copper silicate which is the amorphous equivalent of chrysocolla. To this newly recognized mineral I wish to apply the name *cornuite* in honor of the late Dr. Felix Cornu, of Leoben, Austria, who was practically the first mineralogist to make a sharp distinction between crystalline minerals and their amorphous equivalents.

I have found this mineral on specimens from Globe, Arizona; Bisbee, Arizona; Ludwig, Nevada; Copper Mountain, Alaska, and Collahuasi, Chile. It is usually optically isotropic with n varying from 1.525 to 1.549, but sometimes has irregular, weak double refraction and wavy extinction. It is associated with crystalline chrysocolla and often appears in colloform bands within layers of colloform chrysocolla. It is more readily soluble in hydrochloric acid than chrysocolla and also somewhat softer.

The best specimens of cornuite in my possession are from the mine of the Alaska Consolidated Mining and Smelting Company at Copper Mountain, Prince of Wales Island, Alaska. It occurs as a beautiful bluish-green (Ridgway 42k), transparent, glassy, somewhat banded crust about 1 cm. thick associated with chrysocolla. The index of refraction is 1.549 ± 0.001. I am indebted to my collegue, Dr. G. S. Bohart of the chemistry department, for the following analysis of the Copper Mountain cornuite:

		Ratios
CuO	=42.61	0.537
$\mathrm{Al_2O_3}$	= 0.31	0.004
$\mathrm{SiO_2}$	=34.13	0.566
$\mathrm{H_2O}$	=23.11	1.284

These figures are each the average of two closely agreeing values made upon carefully selected material free from the associated

[1] *Proc. Nat. Acad. Sci.*, II (1916), 8–12.

chrysocolla and all other impurities. The ratios seem to show an excess of both silica and water over that required for the usually accepted empirical formula (H_4CuSiO_5) for chrysocolla, which probably indicates that cornuite is a solid solution of cupric oxid, silica, and water.

Probert[1] describes a "jelly of the most beautiful shades of blue and green" with the following composition: $CuO=47.46$; $SiO_2=21.20$; $H_2O=28.05$; $CaO=1.39$; $Al_2O_3=$tr., from the 200-foot level of Ray Central mine at Ray, Arizona. Here we evidently have cornuite in process of formation.

Chrysocolla is sometimes considered to be an amorphous mineral, but while chrysocolla shows colloidal structures it is microcrystalline (metacolloid), and recently Umpleby[2] has described crystallized chrysocolla from Mackay, Idaho, the indices of refraction of which are $n_\gamma=1.57$ and $n_\alpha=1.46$.

OTHER POSSIBLE VALID AMORPHOUS MINERAL SPECIES

The twenty-three amorphous minerals described in this paper are all believed to be well-established mineral species. Practically all of them are known from several localities and some of them are very common and widely distributed minerals. Although their properties vary somewhat, these minerals are fairly definite and can be recognized by careful work.

There are, however, as many more amorphous minerals which have been described or named, and some of these it may be possible to establish by study of suitable material. I have attempted to enumerate here some of the probable amorphous minerals.

Metastibnite, amorphous Sb_2S_3.
Jordisite, colloidal MoS_2.
Patronite, vanadium sulfid.
Ostwaldite (Buttermilcherz), colloidal AgCl.
Ehrenwerthite, colloidal $Fe_2O_3 \cdot H_2O$.
Amorphous equivalent of fischerite.
Schadeite, amorphous equivalent of plumbogumnite.
Palmerite, hydrous aluminum potassium phosphate.
Yukonite, hydrous calcium iron arsenate.

[1] *Min. and Sci. Press*, CXII (1916), 898.

[2] *Jour. Wash. Acad. Sci.*, IV (1914), 181.

Gummite, alteration product of uraninite.
Glockerite, hydrous ferric sulfate.
Plumboniobite.
Amorphous equivalent of thorite.
Amorphous equivalent of allanite.
Amorphous equivalent of gadolinite.
Amorphous equivalent of yttrotantalite.
Amorphous equivalent of homilite.
Amorphous equivalent of yttrocrasite.
Amorphous equivalent of pyrophyllite.
Greenalite, hydrous ferrous silicate.
Yttrialite.
Neotocite.
Plombierite.
Geolyte (Bodenzeolith), amorphous equivalent of zeolites.
Pochite.

MINERALOIDS (HYDROCARBONS AND GLASSES)

In addition to the foregoing definite amorphous minerals there are several other classes of naturally occurring amorphous substances. I refer to the hydrocarbons and glasses. Shall they be considered as minerals or not? The answer depends upon our definition of the term mineral or mineral species. A mineral (species) is usually defined as a naturally occurring homogeneous substance of definite chemical composition. By common consent the term is limited to the naturally occurring substances, although the specific mineral name is often used for the corresponding artificial substance. No objection can be raised if the word synthetic or artificial is prefixed to the mineral name. In view of the discovery of solid solutions of a kind different from isomorphous mixtures in minerals, the definition given above must be modified so as to read "of more or less definite chemical composition," as suggested by Wherry.[1]

In the case of the hydrocarbons the principal objection against considering them minerals is on account of their organic character. While directly or indirectly the result of organic growth, they are on a somewhat different footing from ordinary plant products. They occur with other minerals in sedimentary rocks and are, in

[1] *Ibid.*, pp. 111–14.

fact, fossil resins and fossil fuels. They are collected and studied by geologists.

The hydrocarbons are by some mineralogists given full rank as minerals, by others omitted entirely, by still others treated in an appendix to minerals. The latter procedure seems to be the safest plan, for they are organic substances, and the typical minerals are certainly inorganic, yet on the other hand they deserve some recognition by the mineralogist. The mineralogist is often called upon to identify them, and they should be described from a mineralogical standpoint.

For these reasons I think the hydrocarbons may be included under Niedzwiedzki's term *mineraloid*.[1] As Niedzwiedzki used this term for all naturally occurring amorphous substances, this changes somewhat the original definition of mineraloid. Such substances as opal, cliachite, limonite, collophane, halloysite, etc., are definite enough to be called minerals even though they are amorphous. The term "mineraloid" seems appropriate for the less definite mineral-like substances.

And in the same category I would also place the natural glasses. As far as I know, glass is not given a place in any modern mineralogical treatise, although the older mineralogists described tachylyte and hyalomelane as mineral species. It is, however, included in some of the determinative tables of the rock-forming minerals found in textbooks on petrography, and for the same reason that it is included in these tables it may be treated as a mineraloid. Natural glass is a homogeneous substance to be identified the same as minerals in general.

Natural glass is, of course, varied in composition in comparison with the various types of igneous rocks, yet the average obsidian is probably not much more varied than some of the amorphous minerals. While glass is scarcely entitled to recognition as a mineral, there are arguments in favor of classifying it as a mineraloid. It may well receive a place in the appendixes of our books on mineralogy. This will call attention to its properties and will aid in its identification, which otherwise might be difficult for a beginner who had studied mineralogy but not petrography.

[1] *Centralblatt f. Min., Geol., u. Pal.*, 1909, pp. 661–63.

Glass, like amorphous substances in general, is in part optically isotropic and in part birefringent. The birefringence is shown in many perlites, some varieties of which are veritable Prince Rupert's drops. Besides the chemical composition, the most important property of glass is its refractive index, which, as has been shown by Stark,[1] varies from about 1.485 for "acid" glasses with 75 per cent silica up to 1.67 for "basic" glasses with 40 per cent silica. Obsidian, perlite, pitchstone, etc., are petrographic terms, but glass as a whole may be treated as a mineraloid from the mineralogical standpoint. Lechateliérite and maskelynite are glasses which are fairly definite in chemical composition.

SUMMARY

Some of the naturally occurring amorphous substances are definite enough to be recognized as mineral species.

The amorphous equivalents of crystalline minerals should be treated as distinctive minerals and should have distinctive names.

About twenty of the more prominent and well-defined amorphous minerals are described and discussed. Most of these minerals are the amorphous equivalents of crystalline minerals.

New names are given to amorphous cadmium sulfid (xanthochroite) and amorphous copper silicate (cornuite) which correspond to sphalerite, greenockite, and chrysocolla respectively.

Arguments are advanced for treating the natural hydrocarbons and natural glasses as mineraloids.

[1] *Min. u. Petr. Mitth.*, XXIII (1904), 536–50.

THE CHAMPLAIN SEA IN THE LAKE ONTARIO BASIN

KIRTLEY F. MATHER
Queen's University, Kingston, Canada

INTRODUCTION

The retreating front of the Labradorian ice sheet late in the Wisconsin glacial stage rested for a time against the northwestern slopes of the Adirondack Mountains. Between the ice front in the upper St. Lawrence Valley and the southern rim of the Ontario basin in New York state, the waters of Lake Iroquois were ponded. The history of this lake, with its outlet down the Mohawk Valley past Rome, New York, has been deciphered by Fairchild, Taylor, Spencer, Coleman, and others. Further withdrawal of the ice margin permitted the escape of the Iroquois waters through "Covey Gulf," southwest of the summit of Covey Hill, the northernmost hill on the west flanks of the Adirondacks, a mile north of the international boundary. The altitude of the Covey outlet at the present time is about 1,000 feet, while that of the Rome outlet is 460 feet, but, according to Fairchild,[1] the altitudes of the two outlets during Iroquois time were very similar, "if not practically identical" (see Fig. 1).

North from Covey Hill the land drops rapidly away to the broad, low valley of the St. Lawrence. As soon, therefore, as the edge of the ice sheet had withdrawn a mile or two farther northward, Lake Iroquois was drained. The water in the Ontario basin and the St. Lawrence Valley rapidly fell to sea-level, for the land stood at a much lower altitude then than now. Differential uplift of the Great Lakes region had commenced long before the extinction of Lake Iroquois, and it is commonly held that the Champlain Sea was then at its maximum extent. It has been more or less unconsciously assumed that the history of these sea-level waters in the upper St. Lawrence Valley was simply a slow but progressive

[1] H. L. Fairchild, "Pleistocene Uplift of New York," *Geol. Soc. Amer. Bull.*, XXVII (1916), 235–62.

withdrawal from the maximum of submergence to the present maximum of emergence. Data now available, however, lead to the conclusions that, when the ice barrier was removed from the St.

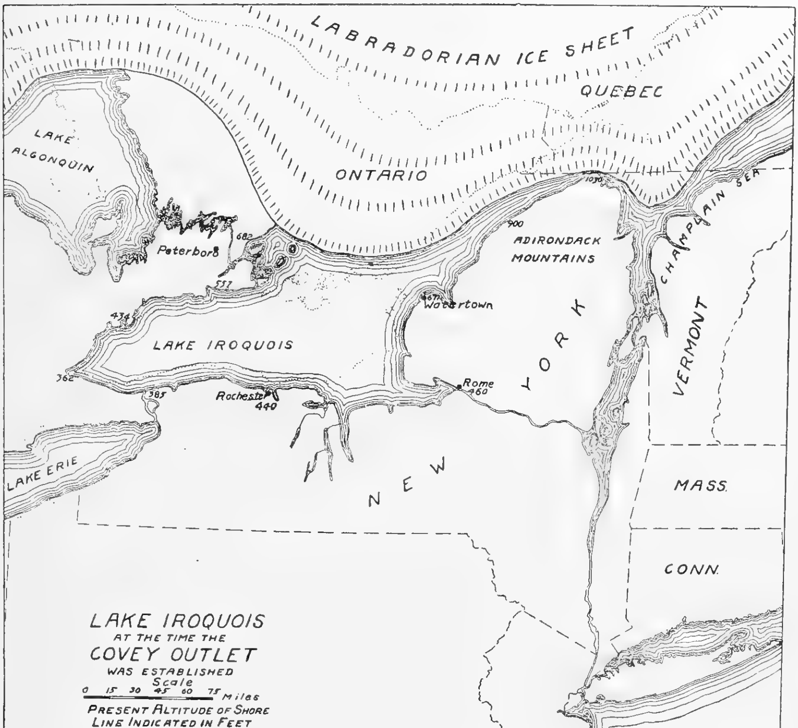

FIG. 1.—A late stage in the history of Lake Iroquois. Lake Algonquin, a portion of which is shown in the Georgian Bay region, overflows through the Fenelon Falls outlet east of Kirkfield, Ontario, and Algonquin River carries its waters to the Rice Lake embayment of Lake Iroquois. The Niagara River outflow from Lake Erie also contributes to Lake Iroquois, which is indicated in its two-outlet stage. Part of its water spills into the Mohawk Valley near Rome, New York, and part falls over the cliff at Covey Gulf, Quebec, into the marine embayment in Champlain Valley. St. Lawrence and Ottawa rivers and parts of the present Great Lakes are indicated by dotted lines. Pleistocene geography based largely upon the work of Fairchild, Coleman, Johnston, and Taylor.

Lawrence Valley north of Covey Hill, the level of the Champlain Sea was far below its maximum height, and that the strand line moved gradually up the valley of the St. Lawrence River and its

tributaries to the position of greatest submergence (Fig. 2) before it began to withdraw toward its present location.

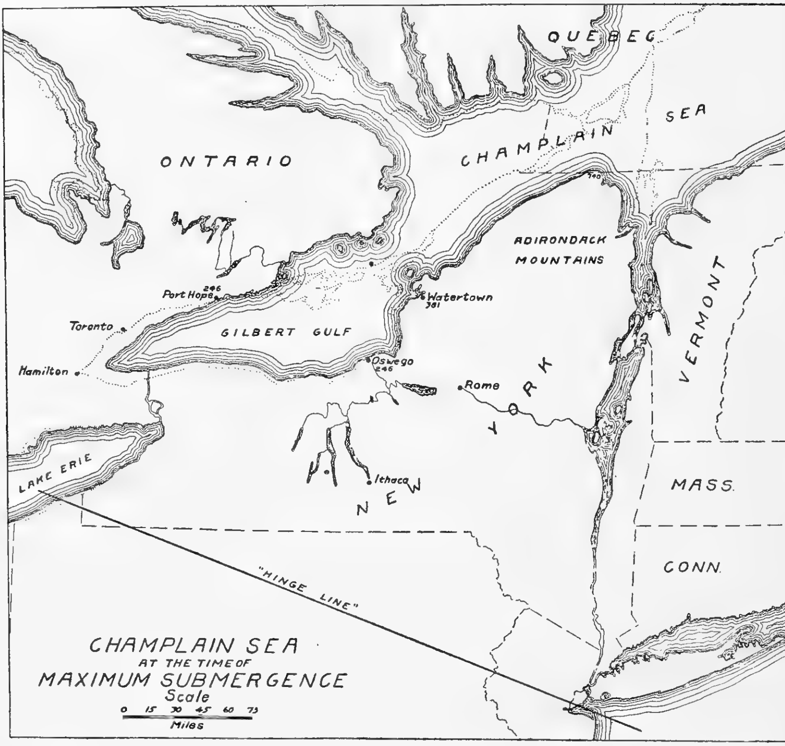

FIG. 2.—The geography of the Ontario-St. Lawrence Valley at the close of Pleistocene time. Champlain Sea is at its maximum extent. Lake Algonquin has been replaced by the Nipissing Great Lakes, which overflow northward down Mattawa and Ottawa rivers. Trent River is a comparatively small stream heading in the Trent chain of lakes and emptying into Gilbert Gulf above Trenton, Ontario. Paleogeography of New York state after Fairchild. Boundaries in Ontario and Quebec generalized and only approximately correct because of scarcity of exact data.

EVIDENCE OF A PROGRESSIVE MARINE SUBMERGENCE OF THE ONTARIO BASIN

Napanee Valley.[1]—Napanee River is one of the many southwesterly flowing streams tributary to Lake Ontario along its

[1] I am indebted to N. B. Davis, of the Department of Mines, Ottawa, for directing my attention to the surficial deposits in Napanee Valley as well as for valuable suggestions made in the field in September, 1916.

northern shore. The river heads in a chain of little lakes which dot the surface of the pre-Cambrian rocks in the central part of Frontenac County, 25 miles north of the east end of Lake Ontario. The lowest of the small lakes is Lake Napanee, 446 feet above sea-level. Thence the river flows across the nearly flat-lying Ordovician limestones which overlap the pre-Cambrian complex, past the towns of Yarker and Napanee to the Bay of Quinte on Lake Ontario (see Fig. 3). From Lake Napanee to Lake Ontario the length of the river is about 24 miles, and its total fall is 200 feet. Throughout this portion of its course Napanee River occupies a pre-Wisconsin youthful valley cut in the limestone cuesta and consequent upon its slope. The valley floor is 75–125 feet below the intervalley upland surface and is bounded by abrupt limestone scarps. Near Yarker the valley walls are scarcely a quarter of a mile apart, but toward Napanee they diverge gradually to a distance of a mile and a half.

The upland surface on either side of Napanee Valley displays abundant evidence of wave and current action. Bedded clays in many places provide a thin veneer of fertile soil over the barren glaciated limestone surface. Elsewhere, bared rock surfaces are studded with the larger bowlders from glacial drift; all the finer products of the glacial mill have been washed away by currents and waves. No distinctive shore features have as yet been observed along the Napanee Valley to mark the upper limit of wave action, but marine or lacustrine clays are present up to altitudes of at least 450 feet in the vicinity of Yarker. At Inverary, 15 miles due east from Yarker and 11 miles north from Kingston, M. B. Baker and I have definitely located the limit of wave action at elevations between 500 and 510 feet above sea-level.

The region is within the area covered by the ice barrier to which Lake Iroquois owed its existence and could not have been freed from its glacial burden until after the extinction of that lake. The wave and current action is therefore that of Gilbert Gulf, the portion of Champlain Sea which occupied the Ontario basin after removal of the ice dam from the Thousand Island region.

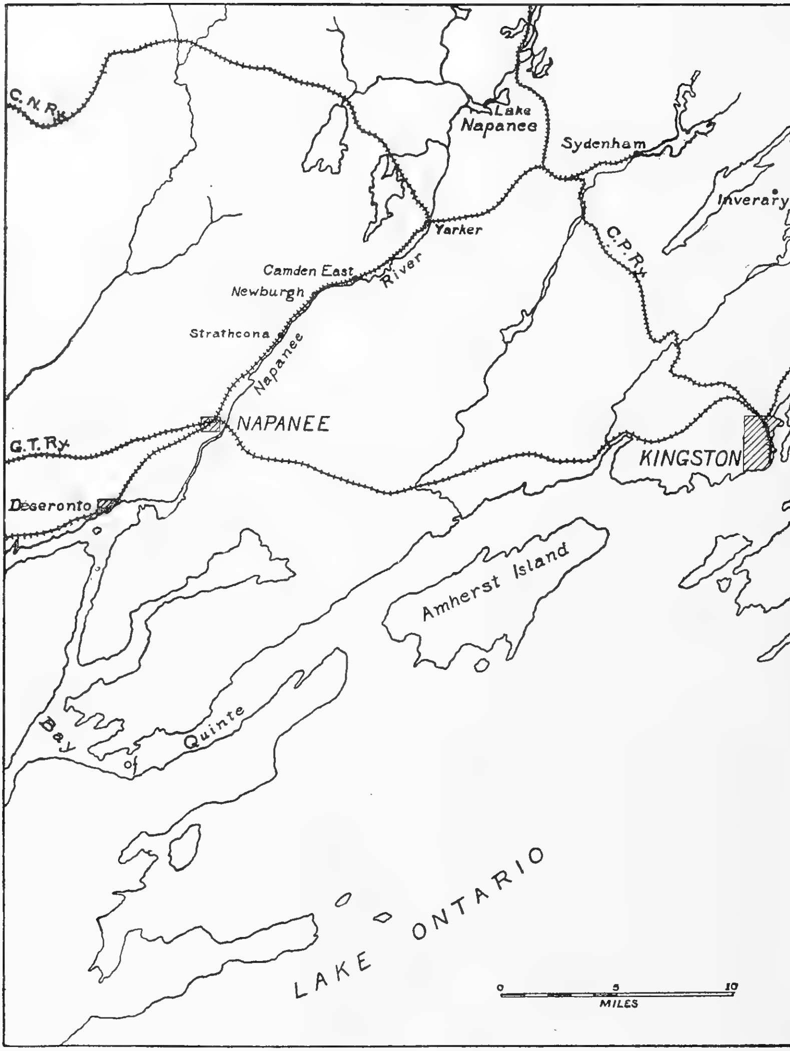

FIG. 3.—Index map of the Kingston-Napanee district, Canada, along the northern shore of the eastern end of Lake Ontario.

Near Ottawa the upper limit of marine submergence has recently been determined[1] to be 690 feet above sea-level. At Belleville the highest marine plane has an altitude of 323 feet.[2] If the gradient is regular between those two localities, the altitude at Yarker would be close to 440 feet. The nearest point on the shore line of Gilbert Gulf in New York, where its features have been mapped by Fairchild, is a small hill $4\frac{1}{2}$ miles southwest from Clayton.[3] This hill is 35 miles S. 70° E. from Yarker; the Gilbert shore encircles it at an elevation slightly above 400 feet. The post-Champlain isobases in this neighborhood run approximately east and west. It is, therefore, quite clear that the Napanee Valley and adjacent uplands were submerged beneath the waters of Gilbert Gulf at least as far northward as Yarker (elevation 425 feet).

That this submergence did not take place when the ice front stood south of the divide at the head of Napanee Valley is clearly indicated by the presence of a valley train of fluvio-glacial gravels within the valley. Remnants of the gravel beds are present at many localities between Yarker and Napanee. Between Newburgh and Strathcona their fluvio-glacial, rather than glacio-lacustrine or glacio-marine, origin is readily apparent. As indicated in Fig. 4, the gravel train has a plane upper surface and its remnants are now distinctly terrace-like. The summit of the valley train is approximately 50 feet above the modern valley flat and has a similar gradient, 8 or 10 feet to the mile. The gravels and sands are irregularly bedded; cross-bedding is common, and assortment according to size of pebbles is very incomplete. Many of the stones are striated or faceted by glacial action. The valley train is in every way a typical sub-aerial fluvio-glacial deposit similar to the comparable outwash gravels of the Fox River Valley in Illinois.

The lowest and most southwesterly remnant of the Napanee valley train is within the city limits of Napanee at an elevation of

[1] W. A. Johnston, "Late Pleistocene Oscillations of Sea-Level in the Ottawa Valley," *Canada Geol. Survey, Mus. Bull. 24*, 1916, p. 5.

[2] F. B. Taylor, "Gilbert Gulf," *U.S. Geol. Survey Mon. 53*, 1915, pp. 445–46; A. P. Coleman, "Marine and Freshwater Beaches of Ontario," *Geol. Soc. Amer. Bull.*, XII (1901), 129–46.

[3] H. L. Fairchild, "Pleistocene Features; Clayton-Lafargeville District," *N.Y. State Mus. Bull. 145*, 1910, pl. 46.

less than 325 feet. In a small gravel pit beside the east abutment of the stone railway bridge the gravels and sands are overlain by bedded clays. Similar bedded clays are present on the floor of the valley eroded into the fluvio-glacial gravel deposits.

At the time of construction of the Napanee valley train the retreating front of the ice sheet had withdrawn less than 10 miles north of Yarker, and the marine plane could not have been over

FIG. 4.—Napanee Valley between Newburgh and Strathcona, Ontario. The cattle in the foreground and the houses and barns in the distance are on the surface of the Napanee valley train. The lower flat in the middle distance is the modern flood-plain of Napanee River. The exposure of fluvio-glacial gravels and sands in the escarpment overlooking the valley flat is in part due to gravel pits and in part to the railroad which parallels the river at the foot of the scarp. Beyond the buildings in the distance, the land rises abruptly to the summit of the limestone cuesta which forms the sky line at the left.

325 feet above present sea-level. Further retreat of the ice cut off the supply of gravel, and dissection of the valley train commenced. Subsequently sea-level waters crept upward and submerged the whole region to at least the 425-foot contour line. In these waters bedded clays accumulated.

Trent Valley.—The anomalous relation between the Trent Valley spillway from Lake Algonquin and the Gilbert Gulf shore features has long been a puzzle to glacialists. The physiographic

features have been described recently by Taylor[1] and Johnston[2] and need not be dwelt upon here. Briefly, Algonquin River carried the overflow from Lake Algonquin to Lake Iroquis and, after its extinction, to Gilbert Gulf. A large delta in the Rice Lake region marks the point at which the river debouched into Lake Iroquois. It is now approximately 620 feet above sea-level. The spillway channel continues down Trent Valley past the Gilbert Gulf shore line (320 feet) to the present level of Lake Ontario (246 feet) near Trenton. The channel below the summit marine plane apparently differs in no way from the portion above that level.

To explain these features by postulating a continuance of the Algonquin River flow until after the lower portion of Trent Valley had been lifted above the level of Champlain Sea is obviously difficult. Neither Taylor nor Johnston is satisfied with that explanation. In the light of the conclusions resulting from the study of Napanee Valley, the difficulties met with in Trent Valley are removed. Algonquin River carried its large volume of water to, and below, the present level of Lake Ontario *before*, rather than *after*, the Trenton neighborhood was submerged beneath sea-level waters. The delta which must have been built at the outlet of the river into Gilbert Gulf is now hidden beneath the lake. Soundings in the Bay of Quinte may some time reveal its hiding-place. By the time the Gilbert strand had crept above the present lake-level retreat of the ice in the Nipissing region had uncovered a new outlet for the upper Great Lakes, and the Lake Algonquin overflow was diverted from the Fenelon Falls outlet.

Confirmatory evidence.—Physiographic features in Napanee and Trent valleys are thus explainable by postulating a positive movement of the strand line in the Ontario basin during the final stages of the waning ice sheet. A similar advance of marine waters in Ottawa Valley has been suggested by Johnston[3] to explain the

[1] F. B. Taylor, "The Pleistocene of Indiana and Michigan and the History of the Great Lakes" (Leverett and Taylor), *U.S. Geol. Survey Mon. 53*, 1915, pp. 445–46.

[2] W. A. Johnston, "The Trent Valley Outlet of Lake Algonquin and the Deformation of the Algonquin Water-Plane in Lake Simcoe District, Ontario," *Canada Geol. Survey Mus. Bull. 23*, 1916.

[3] W. A. Johnston, "Late Pleistocene Oscillations of Sea-Level in the Ottawa Valley," *Canada Geol. Survey Mus. Bull. 24*, 1916.

relations between the fossil-bearing clay zones in the vicinity of Ottawa.

The quaternary deposits near Waterville, Maine, suggest a similar movement of the sea-level there. H. P. Little[1] states that "the main mass of the fluvio-glacial deposits is found in an esker . . . . bordered by marine clays and sands. These overlap the esker and are separated from its gravels by an unconformity considered due to sub-aerial erosion."

CHANGES IN SEA-LEVEL INCIDENT UPON THE WASTING OF THE LABRADORIAN ICE SHEET

The suggestion is an obvious one that the positive movement of the strand line in late Pleistocene times in Northwestern North America may be a result of the return of water to the ocean basins from wasting ice caps. The simple effect of ice melting is, however, complicated in the region under discussion by close proximity to the ice masses. Here, too, sea transgression has been followed by a presumably much greater negative movement of the strand, which has continued nearly or quite to the present time. Barrell's[2] discussion of the various problems involved is especially stimulating in this connection.

Three factors enter into the local problem: elevation of sea-level due to return of water which had been congealed on the land; depression of sea-level due to decreasing gravitative attraction of the ice masses; and uplift of the land due to isostatic, or other, readjustment consequent upon removal of ice burden. None of the three can be exactly evaluated from the data now available, and the effect of the third can be estimated only from field evidence. Mathematical calculations will, however, help to crystallize opinion concerning their interaction.

Woodward's classic contribution[3] to the subject does not exactly meet the situation at hand. His assumptions concerning area and

[1] H. P. Little, "Pleistocene and Post-Pleistocene Geology of Waterville, Maine," abstract of paper presented before the Geological Society of America, December, 1916.

[2] J. Barrell, "Factors in Movements of the Strand Line and Their Results in the Pleistocene and Post-Pleistocene," *Am. Jour. Sci.* (4), XL (1915), 1–22.

[3] R. S. Woodward, "On the Form and Position of the Sea-Level," *U.S. Geol. Survey Bull. 48*, 1888.

thickness of the ice cap were made with the expressed purpose[1] of determining the "maximum upheaval of the water" possible as a result of glacial conditions. I have, therefore, with indispensable assistance from my wife, computed the results obtained from his formulas on the basis of quite different assumptions, which are believed to be more in accord with known data concerning the Labradorian ice sheet.

For mathematical purposes it is fair to assume a circular ice cap with a radius of 14°, or about 966 miles, on the earth's surface and a thickness at its center of 5,000 feet. Let its surface configuration correspond to $n=10$ in Woodward's equation 95.[2] This would give an increasingly rapid slope of the ice surface from center to border as in the following table:

	Slope in Feet per Mile of Ice Surface at Varying Distances, Expressed in Degrees, from Center of Assumed Ice Cap					
Center	4°	6°	8°	10°	12°	Border
.00	.00	.02	.34	2.53	12.95	51.43

From equation 96 it follows that such an ice cap would lower the sea-level 82.5 feet, if all its ice were formed from moisture withdrawn from the ocean. Following the method of Woodward in § 49,[3] we find that the gravitative attraction of this ice sheet would distort the level of the sea so that the disturbed surface along the border of the ice mass would be 136 feet above the undisturbed surface. The average slope of the disturbed surface within one degree of the ice border would be 0.13 feet per mile. If the ice cap were 10,000 feet in thickness at its center, the distortional effect would be twice as great as that of a 5,000-foot cap of the same diameter and surface contour.

There is every reason for believing that the development of the half-dozen ice sheets which covered parts of North America and Europe in Pleistocene times was practically synchronous. The total effect of all must, therefore, be considered in evaluating

[1] *Ibid.*, p. 18.

[2] *Ibid.*, p. 62.

[3] *Ibid.*, pp. 65–66.

resultant changes in sea-level. Daly[1] has presented the requisite data for estimating the area, ice-covered during the Pleistocene, which is now freed from its glacial burden. If the ice averaged 5,000 feet in thickness over this area, the sea-level would have been lowered about 235 feet by abstraction of water. In comparing this figure with the 136 feet of elevation at the border of the assumed Labradorian ice sheet it should be remembered that a considerable body of Pleistocene ice existed at distances of more than 45° from its border and would have exerted an attraction in the opposite direction.

It seems safe to conclude that at no time or place was the gravitative attraction of a Pleistocene ice cap powerful enough to elevate sea-water at its border sufficiently to overcome the lowering of sea-level due to withdrawal of water from the sea. This means that so far as these two factors are concerned the movement of the strand line was everywhere negative during the time of advancing ice and positive during the waning stages.[2] Near the ice borders the movement was in each case less in amount than in lower latitudes, but its direction was the same. Disregarding secular adjustment within the earth, the retreat of the Labradorian ice front from Covey Hill northward must have resulted in a progressively more extensive submergence of the St. Lawrence-Ontario Valley.

For present purposes it is unnecessary to make any inquiry into the causes of the differential uplift of northern lands which is known to have occurred since retreat of the Labradorian ice sheet began. It is, however, essential to know the time relations between the withdrawal of the ice and the readjustments which so convincingly appear to be of an isostatic nature. Did the land mass respond so quickly that secular movement entirely compensated the rising sea-level and thus maintained a stationary, or even a retreating, strand-line? Or did crustal deformation lag behind unloading of the ice burden sufficiently to permit an upward movement of the sea-level to precede the upward movement of the land?

[1] R. A. Daly, "The Glacial-Control Theory of Coral Reefs," *Proc. Amer. Acad. Arts and Sci.*, L (1915), 172.

[2] Cf. C. Schuchert, "The Problem of Continental Fracturing and Diastrophism in Oceanica," *Amer. Jour. Sci.* (4), XLIII (1916), 92, 93.

The philosophy of diastrophism is not sharply enough defined to permit an a priori answer to this question. On the one hand are many data, such as those obtained by Michelson[1] in his study of tides, which indicate quick response to external strain; on the other hand are just as many, if not more, facts, such as those concerning periodicity of orogenic episodes, which indicate the ability of the earth to delay adjustment for some time after strains begin to accumulate.

Field evidence in the Great Lakes region strongly suggests considerable lag of continental uplift behind ice removal. Post-glacial marine fossils in the Hudson's Bay drainage basin occur at elevations at least as great as 450 feet[2] and indicate uplift of that amount since the Labradorian ice sheet shrank to a diameter of less than two or three hundred miles. The highest shore line of the Champlain Sea rises toward the north at an average gradient of more than $2\frac{1}{2}$ feet per mile and is essentially parallel to the Iroquois strand—sufficient proof in itself that the uplift of the St. Lawrence region, in greater part at least, lagged considerably after removal of the ice load.

The facts concerning Quaternary diastrophism in the region covered by the Labradorian ice sheet seem to be in complete agreement with the conclusion reached from field evidence in Napanee Valley, namely, that the late Wisconsin and Recent uplift did not cause the marine strand to retreat until after an appreciable interval of sea-advance had resulted from the melting of the ice.[3]

[1] A. A. Michelson, "Preliminary Results of Measurements of the Rigidity of the Earth," *Jour. Geol.*, XXII (1914), 97–130.

[2] A. P. Coleman, "Lake Ojibway; Last of the Great Glacial Lakes," *Ontario Bur. Mines, Ann. Rep.*, XVIII (1909), 284–93.

[3] In determining the amount of deformation affecting the shore lines of an inclosed body of water, such as Lake Iroquois, during its existence, the distortion of its surface by gravitative attraction should by no means be disregarded. Retreat of the ice front will, in effect, carry the inclined plane of the water surface northward and at the same time cause it to approach more closely a horizontal position. The result will be splitting of beaches north of the lake's outlet, and drowning of the older shore features south of the outlet. This apparent, though not real, warping of the basin was in many cases of sufficient amount to be of quantitative importance. One reason why the Nipissing beach, although tilted, departs but little from a true plane, while the Algonquin and earlier beaches are warped as well as tilted, is that Lake Nipissing was not a marginal glacial lake, as were its predecessors.

SUMMARY

Withdrawal from the Thousand Island region of the Labradorian ice barrier responsible for the existence of Lake Iroquois was followed by accumulation of fluvio-glacial gravels in Napanee Valley. The pro-glacial stream descended to a locality which is now less than 325 feet above sea-level before it debouched into Gilbert Gulf, an arm of the Champlain Sea. At the same time Algonquin River carried the overflow from Lake Algonquin down Trent Valley past Trenton, Ontario, to an outlet which is now beneath the waters of Lake Ontario.

The melting-back of the ice front from Covey Hill toward the Height of Land was contemporaneous with a positive movement of the strand-line which carried marine waters toward the head of the Ontario basin and drowned the Napanee and Trent valleys. The positive movement of the strand-line was followed by a negative movement, which began approximately at the time of complete disappearance of Labradorian ice and has continued nearly or quite to the present time.

Disregarding crustal movement, the waning of Pleistocene ice caps would result in a world-wide transgression of the sea as its volume was increased by the return of water temporarily abstracted to form the ice masses. In high latitudes the amount of movement of sea-level would be much less than in low, because of gravitative attraction of the ice, but everywhere the direction of movement would be the same.

Secular adjustment following removal of ice load was delayed in the Ontario-St. Lawrence region long enough to permit a stage of sea-advance before upward tilting overcame the effect of ice-melting and the stage of sea-retreat was reached.

THE RELATIONSHIPS OF THE FOSSIL BIRD *PALAEOCHENÖIDES MIOCEANUS*

ALEXANDER WETMORE
U. S. Biological Survey, Washington, D.C.

In a recent number of the *Geological Magazine*[1] Dr. R. W. Shufeldt described and figured the fossilized distal end of the right femur of a bird from South Carolina, proposing for it the name *Palaeochenöides mioceanus.* This Dr. Shufeldt considered as representing a large anserine form. Through the courtesy of Dr. O. P. Hay, I have had opportunity of comparing this type, and after careful study am forced to disagree with Dr. Shufeldt as to the affinities of the species represented. After careful comparison with many specimens I am convinced that the fragment does not come from an anserine bird, but that it represents a large steganopod, related (though not closely) to our modern brown pelicans.

When the specimen was first examined, the popliteal area of the bone was obscured by matrix that covered and obliterated contours and slight depressions. This was carefully removed, and these characters made fully visible (Fig. 1). Though at first glance there are certain resemblances to the swans, these characters are found to be superficial and to lose their value upon careful study. The anseriform species available that show certain resemblances to *Palaeochenöides* are the following: *Olor buccinator*, *O. americanus*, *O. cygnus*, *Branta canadensis*, *Chen caerulescens*, and *Dendrocygna autumnalis*. A considerable number of other species have been examined, but have been found to resemble the above closely or to be so different as not to be pertinent in the present case. In the Steganopodes the following have been utilized: *Phaëthon aethereus*, *Fregata magnificens*, *Sula leucogastra*, *S. bassana*, *S. serrator*, *Pelecanus fuscus*, and *P. onocrotalus*. The cormorants and darters are highly

[1] 1916, pp. 343–47 (Pl. XV).

specialized, so that, though several species of *Phalacrocorax*, *Nannopterum*, and two species of *Anhinga* were examined, they were not directly comparable. In the following table I have drawn up in parallel columns the salient differences in the distal end of the

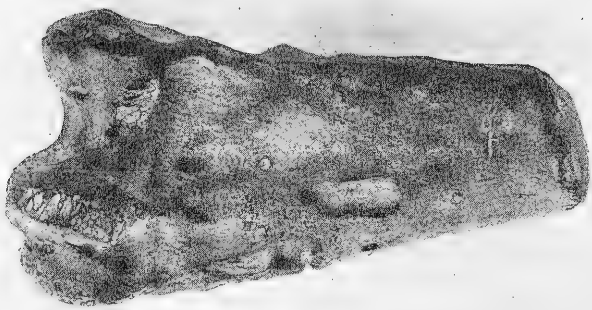

FIG. 1.—Lower surface of distal portion of femur (type) of *Palaeochenöides mioceanus.*

femur in the species enumerated in the two groups. An asterisk indicates which group *Palaeochenöides* resembles in the characters designated.

Anseres	Steganopodes
1. Intercondylar notch deep, narrow.*	1. Intercondylar notch more shallow, broader.
2. Femur non-pneumatic.	2. Femur pneumatic.*
3. Condyles well elevated on dorsal surface, rising abruptly from shaft.	3. Condyles little elevated on dorsal surface, merging in a long gradual slope into shaft.*
4. Ventral surface of femur behind condyles more rounded, lateral margins strongly rounded.	4. Ventral surface of femur behind condyles flattened, lateral margins angular or very slightly rounded.*
5. Tuberosity above fibular facet of outer condyle extending at an angle across outer third of shaft.	5. Tuberosity above fibular facet of outer condyle lateral, following line of shaft.*

It is seen that in four of these major differences *Palaeochenöides* agrees with the Steganopodes, while in only one does it approach the Anseres. Other differences of less constant value are present between the two groups. In most of the anserine birds the con-

dyles project farther on the ventral surface, and the distal end of the femur is greatly expanded at the condyles, the shaft being slender in comparison. In the Steganopodes (save in the Phalacrocoracidae) the condyles are less produced ventrally and there is a gradual broadening of the shaft until it merges gradually into the condyles. In the Anseriformes, in general, the lateral diameter of the shaft of the femur where the expansion for condylar support ceases is less than one-half the greatest lateral width through the condyles (the measurement of the shaft in this case not being absolutely its smallest diameter, but usually the breadth at a point one-third of the length of the femur from its distal extremity). In the Sulidae, the brown pelicans, and the snake-birds this diameter is more than one-half of the condylar width. Some cormorants have it greater (*P. albiventris*), and some less. In all of these points *Palaeochenöides* resembles the totipalmate birds, and it is referred without question to the Steganopodes. The distal end of the femur representing *Palaeochenöides*, while similar to that of our present-day pelicans, differs in having a posterior pneumatic foramen, the popliteal space divided by a rounded elongate ridge (extending at an angle posteriorly from the pneumatic fossa), the outer condyle broader and stronger, and the intercondylar channel deeper and more narrow, with no depression evident on the dorsal face of the shaft immediately posterior to the origin of the condylar ridges. Should more of the skeleton become known, it may eventually be placed in a separate family. If we may venture to base theory upon this one fragment, *Palaeochenöides* was a pelican-like bird somewhat larger than *Pelecanus erythrorhynchos* or *P. onocrotalus*, as the portion of the femur representing it seems to indicate that the bone in its entirety was somewhat larger and heavier than the femur in these two species. In its appearance this bone seems, too, to show certain resemblances to the Sulidae and remotely to the Anhingidae and the Phalacrocoracidae. Hence, while *Palaeochenöides* will stand as a milepost in the line of descent of the pelicans, it brings down to us suggestions of generalized development indicating ancient relationships of pelicans to gannets and more remotely to the cormorant-anhinga branch of the totipalmates.

A STUDY OF THE FAUNAS OF THE RESIDUAL MISSISSIPPIAN OF PHELPS COUNTY (CENTRAL OZARK REGION), MISSOURI

JOSIAH BRIDGE
University of Chicago

In the reports of the early writers on the geology of the Ozark region in Missouri mention is made of scattered patches of bowlders containing fossils of "Chemung age" occurring in counties where no rocks of this age are in place or where they are but sparingly represented.

The investigations of Shumard, Meek, and Broadhead for the Missouri Bureau of Geology and Mines, between 1855 and 1871, published in 1873, mention such bowlders from Maries, Miller, Morgan, Phelps, Wright, and Ozark counties.[1] This list of localities is doubtless incomplete, since much of the region was not examined by these workers. Meek assigned these bowlders to the Lower Carboniferous, but Shumard and Broadhead employ the older term Chemung. Shortly before the publication of the report, the so-called "Chemung Group" of the older Missouri geologists was shown to be Lower Carboniferous, and in a footnote in Shumard's report on Ozark County,[2] he states that the term Chemung as employed in these reports is to be understood to mean Lower Carboniferous.

Broadhead again mentions these deposits in his report for 1873–74, as follows: "Fragmentary outliers of this group [Chouteau] are occasionally found capping the ridges near the Arkansas line."[3]

[1] Missouri Bur. of Geol. and Mines, *Reports of the Geological Survey of the State of Missouri*, 1855–71 (1873). See reports of the various counties named above.

[2] *Ibid.*, p. 190.

[3] G. C. Broadhead in Missouri Bur. of Geol. and Mines, *Reports of the Geological Survey of the State of Missouri*, 1873–74 (1874), p. 27.

In 1898 Broadhead, writing on the Ozark uplift and the growth of the Missouri Paleozoic,[1] states that "beds of Chouteau limestone" have been found in Wright and Maries counties, and that the Burlington limestone has been recognized in Morgan, Benton, and Hickory counties, from which he concludes that at least the western half of the Ozark uplift was submerged during the Lower Carboniferous period.

The work of the present Missouri Bureau of Geology and Mines has given some additional information concerning the distribution of these deposits. Marbut,[2] Ball and Smith,[3] Van Horn and Buckley,[4] and Lee,[5] working in different areas in the northwestern part of the Ozark region, have mentioned these deposits, but up to the present time no careful study has been made either of the distribution of this residual material or of its faunal content. In the literature it is commonly referred to as Chouteau or Burlington. In some localities these deposits are termed "residual Boone Cherts."

The purpose of the present paper is to present the results of a careful study of the faunas contained in a number of these bowlders. The bowlders which have furnished the material for this investigation were all collected within an area of about forty square miles situated in the extreme northeastern part of the Rolla quadrangle and the adjacent portion of Phelps County.

This area is a small plateau the summit of which is capped by resistant formations. The physiography and general geology of the region have been well described by Lee[6] and need not be rediscussed here. The entire plateau is underlain by the Jefferson City dolomite of Canadian age, and lying unconformably upon

[1] G. C. Broadhead, "The Ozark Uplift and the Growth of the Missouri Paleozoic," Missouri Bur. of Geol. and Mines, Vol. XII (1898), *Areal Geology*, p. 398.

[2] C. F. Marbut, "Geology of Morgan County," Missouri Bur. of Geol. and Mines, Vol. VII (1907), 2d ser., pp. 49–51.

[3] S. H. Ball and A. F. Smith, "Geology of Miller County," Missouri Bur. Geol. and Mines, Vol. I (1903), 2d ser., pp. 82–89.

[4] F. H. Van Horn and E. R. Buckley, "Geology of Moniteau County," Missouri Bur. of Geol. and Mines, Vol. III (1905), 2d ser., pp. 44–58.

[5] Wallace Lee, "Geology of the Rolla Quadrangle," Missouri Bur. of Geol. and Mines, Vol. XII (1913), 2d ser., pp. 41–43.

[6] *Ibid.*, pp. 52–58, 13–40.

this are patches of non-fossiliferous sandstone and fire clays, which on lithologic grounds are classed as basal Pennsylvanian. The area covered by these Pennsylvanian deposits is not definitely known, but recent work has shown that its extent is much greater than has heretofore been supposed. It probably caps the divide almost continuously from Rolla to Cuba and for a considerable distance northeast of Cuba. Around the edges of this plateau where the Pennsylvanian is wanting, but where the Jefferson City formation is still in place, there are found small areas which are covered with Mississippian bowlders. They rarely cover more than a few acres and may or may not be associated with similar deposits of Pennsylvanian age. They have an average vertical distribution of about thirty-five feet and a maximum of eighty feet. The total relief of the Rolla area is about five hundred feet, but the bowlder patches are confined to the upper two hundred feet. They occur at lower levels in the northern part of the area, owing to the slight dip of the underlying formations.

The bowlders almost invariably occur on the hillsides or in the heads of small ravines. A few patches have been found upon the hilltops, but in every case the crest of that particular hill was below the general summit-level. In the places where one of the bowlder areas is associated with a small outlier of Pennsylvanian it may completely encircle it, but in most cases forms a fringe on one side only, which would seem to indicate that these bowlder areas were localized in some manner before the deposition of the Pennsylvanian.

The exact nature of the Mississippian-Pennsylvanian unconformity is still doubtful. Outliers of Mississippian rocks occur in some parts of the Ozark region, but up to the present none have been found in this area. Small isolated patches of stratified Mississippian may be buried beneath the Pennsylvanian, but at the present time no such occurrences have been reported. At one locality fragments of the Mississippian have been found in the basal conglomerate of the Pennsylvanian,[1] but such association is not common. It may be that these patches of bowlders are the remnants of small outliers which have been reduced to this stage since the

[1] Wallace Lee, *op. cit.*, p. 44.

erosion of the Pennsylvanian, but there is also the possibility that these deposits were in the bowlder form before the invasion of the Pennsylvanian seas. In either case the character of the bowlders seems to indicate that they have not been moved far from their place of origin, if they have been moved at all.

Lithologically the bowlders fall into a number of well-marked groups. The more abundant ones are of course, dense, quartzitic sandstone, which in its original state was probably a calcareous sandstone. In their present condition the calcium carbonate content has been completely removed by leaching, and thin sections show them to be made up entirely of clear quartz grains exhibiting little evidence of secondary growth. The interior of these bowlders is semi-translucent, bluish white in color, and the rock is quite hard and dense, but the more weathered, external portions are extremely porous and deeply stained with iron oxide. They are abundantly fossiliferous, but the fossils are scattered irregularly through the rock with no arrangement that would suggest bedding. Associated with the quartzitic bowlders are masses of soft, friable, fine-grained white sandstone, which are somewhat leached and in which the more weathered phases are deeply stained with iron oxide. Otherwise the rock is but little altered. The fossils of these sandstone masses are arranged in parallel bands, which probably correspond to the bedding planes of the formation.

Bowlders of chert are also abundant. Some are practically unweathered, others are so completely leached that they powder under the hammer. For the most part they are white or pale bluish white in color, and, like the sandstone bowlders, they are stained with iron oxide in proportion to the amount of weathering which they have undergone. At one locality a single chert bowlder has been found which is of a pale pink color, the color appearing to be original.

Lee[1] has mentioned that bowlders of siliceous oölite of Mississippian age occur at one locality associated with bowlders of the quartzitic type. A careful examination of such oölite bowlders from this and other localities where they are associated with residual

[1] *Ibid.*, p. 42.

Mississippian deposits has failed to disclose any determinable Mississippian fossils. Some of the oölite is conglomeratic, containing small angular chert pebbles, and much of it contains small cavities, some rounded, others angular, which simulate the impression of poorly preserved fossils. Lee has suggested that this oölite is the possible equivalent of the Short Creek oölite of southwestern Missouri. The writer has not seen Lee's collections from the fossiliferous oölite, and his own observations have not confirmed Lee's. Bowlders of siliceous oölite are abundant in the residual material over a large part of this area. There are beds of it in the Jefferson City formation, and some oölite bowlders have been found which contain Canadian fossils. On the other hand, many of the oölite bowlders are weathered and stained with iron oxide in much the same manner as are the Mississippian bowlders, while others do not seem to have been weathered in this manner.

The association of the different types of bowlders seems to follow no general rule. In some localities they consist exclusively of sandstones, while in others chert predominates, but in nearly every case examples of all the easily recognized lithologic types are to be found together.

The fossils are in most cases preserved as molds of the exterior and as casts of the interior. In rare instances the shell itself, together with the internal structures, has been completely silicified. In many examples the molds and internal casts preserve the markings of the original with great fidelity, and excellent squeezes may be obtained from them. Some difficulty has been experienced in correlating the mold with the internal cast, for, strangely enough, when one surface is well preserved, the other often is not.

The material used in the preparation of this paper has come from three sources: (1) a collection belonging to the Department of Geology of the Missouri School of Mines and Metallurgy, lent by Professor Cox and Professor Dake; (2) some collections belonging to the Missouri Bureau of Geology and Mines, lent by Mr. Buehler; and (3) a number of collections made by the writer and his friends. These were made while the writer was connected with the Missouri School of Mines and are the property of that institution.

At the outset it was realized that in order to get decisive results the faunas of each individual bowlder must be kept together so that the natural association of species might be determined. This has been done, and a record of the localities from which the individual bowlders have come has also been kept. The original collection of the School of Mines was made without regard to the first factor and with but slight regard to the second, so that, while it contains many fine specimens which have been of great value in making comparisons, it has been useless for exact stratigraphic purposes. The collections of the Missouri Survey and those made by the writer were made with both of the above-mentioned points in view, and all of the conclusions drawn from this study are based upon the faunas which they have yielded. Numbers have been assigned to the several localities from which collections have been made, and these, together with the location, are given in the accompanying list.

Register of Localities, Phelps County, Missouri

1. T. 38 N., R. 8 W., N.E. $\frac{1}{4}$, S.E. $\frac{1}{4}$, Sec. 36.
2. T. 38 N., R. 8 W., N.E. $\frac{1}{4}$, N.E. $\frac{1}{4}$, Sec. 36.
3. T. 38 N., R. 8 W., S.W. $\frac{1}{4}$, S.E. $\frac{1}{4}$, Sec. 25.
4. T. 37 N., R. 8 W., N.W. $\frac{1}{4}$, S.W. $\frac{1}{4}$, Sec. 26.
5. T. 37 N., R. 8 W., Center line S. $\frac{1}{2}$, Sec. 25.
6. T. 38 N., R. 8 W., S.E. $\frac{1}{4}$, S.W. $\frac{1}{4}$; Sec. 27.
7. T. 38 N., R. 8 W., W. $\frac{1}{2}$, S.W. $\frac{1}{4}$, Sec. 27.
8. T. 37 N., R. 8 W., S.W. $\frac{1}{4}$, S.W. $\frac{1}{4}$, Sec. 24 and adjoining corners in Secs. 24 and 25.
9. T. 38 N., R. 8 W., S.W. $\frac{1}{4}$, S.E. $\frac{1}{4}$, Sec. 35.
10. T. 38 N., R. 8 W., N.W. corner N.W. $\frac{1}{4}$, N.E. $\frac{1}{4}$, Sec. 35.
11. T. 38 N., R. 8 W., N.W. $\frac{1}{4}$, N.W. $\frac{1}{4}$, Sec. 36.
12. T. 38 N., R. 8 W., Center S.E. $\frac{1}{4}$, Sec. 26.

MARIES COUNTY, MISSOURI

1. T. 40 N., R. 8 W., Sec. 7.

Lee's map shows the location of most of the localities listed above.

The oldest Mississippian fauna which this area has yielded is contained in the bowlder of pink chert, mentioned on page 561. The bowlder is case-hardened and stained with iron oxide to the

depth of about one-eighth of an inch. It is somewhat leached, but otherwise is scarcely weathered. The following fauna was obtained:

FAUNA OF BOWLDER 28, LOCALITY 7

Coelenterata
    Zaphrentidae
        Gen.? sp.?
    Cyathaxonidae
        Cyathaxonia sp.
Echinodermata
    Platycrinus sp. (stem fragments)
    Unidentified stem and other fragments
Molluscoidea
    Fenestella burlingtonensis Ulr.?
    Rhombopora sp.
    **Productus sampsoni* Weller?
    Rhipidomella diminutiva Rowley
    Camarotoechia tuta (Miller)
    **Dielasma fernglenensis* Weller
    Terebratuloid shell gen.? sp.? (3 forms)
    **Cyrtina burlingtonensis* Rowley
    Spirifer sp. (small form, probably young shell)
    **Spiriferina subtexta* White
    **Brachythyris fernglenensis* Weller?
    Ambocoelia levicula Rowley
    Ambocoelia sp.
    Reticularia cooperensis (Swallow)
    **Ptychospira sexplicata* (W. &. W.)
    **Athyris lamellosa* (Leveille)
    **Cliothyridina glenparkensis* Weller?

A comparison of this fauna with the Fern Glen fauna described by Weller[1] shows that the two have very close relationships. While the fauna of this bowlder is not as large as that of the Fern Glen, the majority of its determined forms are identical with, or closely related to, Fern Glen species. In the faunal list given above the species occurring in the Fern Glen fauna have been designated by an asterisk. Of the ten certainly identified brachiopods, six are recorded in the Fern Glen fauna, and three others, doubtfully identified, are also represented in the Fern Glen. The

[1] Stuart Weller, "Kinderhook Faunal Studies, V, The Fauna of the Fern Glen Formation," *Bul. Geol. Soc. Amer.*, XX (1909), 265–332.

genus *Cyathaxonia* is abundantly represented in the Fern Glen fauna, and *Platycrinus* and *Rhipidomella* also occur. *Camarotoechia tuta* and *Ambocoelia levicula* are both found in the Lower Burlington limestone, while *Reticularia cooperensis* appears to be a survival from the late Kinderhook. The relationships of this fauna are so definite that there is no hesitation in calling it the equivalent of the Fern Glen fauna.

A somewhat younger fauna has been obtained from a number of quartzitic bowlders, and the faunas of the four best bowlders containing this fauna have been combined to form the list given in Table I.

A comparison of the four faunas listed (p. 566) shows that they are closely related. Only one species is common to all four faunas, but three species are common to faunas Nos. 3 and 5, seven to faunas Nos. 31 and 5, five to faunas Nos. 17 and 5, etc. The bowlders in which these faunas were contained were all small, and this would partially account for some of the diversity.

The affinities of these faunas are with the Burlington rather than with the Kinderhook. Many of the species are common to the Upper Kinderhook and the Lower Burlington, and recent work has suggested that some beds which have commonly been referred to the upper part of the Kinderhook are more nearly related to the base of the Burlington. This fauna is not the equivalent of the Fern Glen fauna just described; neither is it the exact equivalent of the fauna of the Burlington White Chert from Louisiana, Missouri, but appears to be intermediate between the two. Very few faunas have been described from this horizon, and, until more definite work is done on this portion of the Mississippian, a more exact correlation cannot be made.

The faunas of the eight bowlders listed in Table II have much in common, and undoubtedly are from a common horizon.

Of the 72 forms listed in Table II, 50 are found in the Burlington of various localities, and at least 11 more occur in the Fern Glen and in beds of equivalent age. A few forms hitherto reported only from the Upper Kinderhook and Chouteau—*Chonophyllum sedaliense*, *Reticularia cooperensis*, *Productus blairi*, and *Hustedia circularis*—are also recorded. Some of these are definitely identified;

the presence of others is doubtful, but their presence does not affect the correlation of the faunas. Some of the bryozoans listed

TABLE I

Locality No. Bowlder No.	7 31	10 3	10 5	10 17
Coelenterata				
Zaphrentis calceola W. & W.	x	x	x	x
Echinodermata				
Cryptoblastus melo O. & S.			x	
Platycrinus ? sp.				x
Undet. crinoid base			x	
Molluscoidea				
Fenestella cf. *F. exigua* Ulr.				x
Polypora sp.			x	
Schellwienella sp.	x		x	
Chonetes multicosta Winchell			x	x
Chonetes sp. undesc.		x		
Productus sampsoni Weller			x	
Productus fernglenensis Weller	x		?	
Productus burlingtonensis Hall			?	
Productus sp.			x	
Rhipidomella diminutiva Rowley	x	x		
Schizophoria chouteauensis Weller	x			
Schizophoria swallovi (Hall)	x			
Schizophoria subelliptica (W. & W.)		x		
Schizophoria sp.			x	
Camarotoechia sp.			x	x
Rhynchopora sp.			x	
Cranaena globosa Weller				x
Dielasma osceolensis Weller ?				x
Spiriferina sp.		x		
Spirifer osagensis Swallow	x	x	x	
Spirifer vernonensis Swallow	x		x	
Spirifer latior Swallow	x			
Spirifer louisianensis Rowley	x		x	x
Spirifer legrandensis Weller	cf.			
Spirifer platynotus Weller	?	x		
Spirifer biplicoides Weller			x	x
Spirifer sp. nov.			x	
Spirifer sp.			x	
Spirifer sp.			x	
Brachythyris ? sp.	x			
Syringothyris sp.	x			
Ambocoelia levicula Rowley		x	x	
Nucleospira obesa Rowley	x			
Cliothyridina tenuilineata (Rowley)				x
Mollusca				
Conocardium sp. nov.	x		x	
Euomphalus latus Hall	x	x		
Platyceras obliquus (Keyes)				x
Orthonychia sp.	x			
Igoceras ? sp.			x	
Arthropoda				
Phillipsia meramecensis Shumard				x

TABLE II

Locality No. Bowlder No.	1 MGS 2	4 101	5 100	10 4	10 2	10 27	1 MGS 1	12 MGS 3
Coelenterata								
Zaphrentis calceola W. & W.	x	x		x			x	x
Zaphrentis sp. undet.								x
Zaphrentis sp. undet.								x
Zaphrentis sp. undet.							x	
Triplophyllum centralis (E. & H.)		x						
Triplophyllum sp		x						
Amplexus fragilis White & St. John		x						
Chonophyllum sedaliense White		x						
Echinodermata								
Cryptoblastus melo O. & S.				x			x	x
Batocrinus? tuberculatus? W. & S.						x		
Aorocrinus?? sp							x	
Actinocrinidae gen.? sp.?							x	
Platycrinus sculptus Hall		cf.						
Platycrinus sp. (several)	3	x	x		x		x	2
Crinoid fragments, plates, stems	x	x	x	x	x	x	x	x
Molluscoidea								
Fenestella filistriata Ulr.	?					?		
Fenestella multispinosa Ulr.	?		?					
Fenestella compressa var. *elongata* Cumings	x	x						x
Fenestella burlingtonensis Ulr.						?		
Fenestella? sp						x		
Fenestella? sp								x
Fenestella? sp	x							
Hemitrypa? sp	x							
Fenestelloid gen., sp	x							
Rhombopora sp	x							
Glyptopora sp								x
Leptaena analoga (Phillips)		x						
Schellwienella alternata Weller	x							
Schellwienella inflata W. &. W.	cf.	x						
Schellwienella burlingtonensis Weller		x		x				x
Schellwienella or *Streptorhynchus* sp		x		x				x
Streptorhynchus sp		x						
Chonetes glenparkensis Weller	x							
Chonetes multicosta Winchell				x				x
Chonetes illinoisensis Worthen							x	x
Chonetes logani N. & P.								x
Chonetes sp. nov		x						
Chonetes sp	x							
Chonetes sp						x		
Productella concentrica (Hall)		x					x	
Productella millespinosa Girty						x		
Productus ovatus Hall	x					?		x

TABLE II—*Continued*

Locality No. / Bowlder No.	1 / MGS 2	4 / 101	5 / 100	10 / 4	10 / 2	10 / 27	1 / MGS 1	12 / MGS 3
Molluscoidea—*Continued*								
Productus sampsoni Weller	x						x	x
Productus sedaliensis Weller	cf.							cf.
Productus blairi Miller	cf.							
Productus burlingtonensis Hall		x						x
Productus fernglenesis Weller		?					?	
Productus sp.								x
Rhipidomella burlingtonensis (Hall)	x						x	x & cf.
Rhipidomella diminutiva Rowley	x	x						x & cf.
Rhipidomella thiemei (White)							x	
Rhipidomella sp.		x						
Schizophoria chouteauensis Weller	cf.							x
Schizophoria swallovi (Hall)		x						
Schizophoria poststriatula Weller								x
Camarophoria bisinuata (Rowley)						x		
Camarotoechia tuta (Miller)		x						x
Camarotoechia sp.							x	
Rhynchopora persinuata (Winchell)								x
Centronelloidea rowleyi (Worthen)		x					x	
Cranaena globosa Weller							x	
Dielasma chouteauensis Weller	x							
Dielasma osceolensis Weller		x						
Dielasma sp.	x							
Spiriferina subtexta White	x	x				x	x	
Spiriferina solidirostris White								x
Spiriferina sp.					x	x		
Delthyris novamexicana (Miller)						?		
Spirifer louisianensis Rowley	x	x	x				x	x
Spirifer vernonensis Swallow	?	x					?	x
Spirifer insculptus Rowley	x							
Spirifer platynotus Weller	?	?						?
Spirifer biplicoides Weller		x						x
Spirifer gregeri Weller		x				?		
Spirifer osagensis Swallow		x					x	x
Spirifer forbesi N. & P.				x			x	x
Spirifer carinatus Rowley							?	
Spirifer rowleyi Weller								x
Spirifer sp.		x						
Spirifer sp.		x						
Spirifer sp.								3
Spirifer sp. (young shell)							x	x
Spirifer? sp.						x		
Brachythyris chouteauensis Weller	x						x	x
Syringothyris sp.								x

TABLE II—*Concluded*

Locality No. / Bowlder No.	1 MGS 2	4 101	5 100	10 4	10 2	10 27	1 MGS 1	12 MGS 3
Mulloscoidea—*Continued*								
Pseudosyrinx missouriensis Weller						x		
Ambocoelia levicula Rowley	x		x		x	?		
Reticularia cooperensis (Swallow)	x					x	x	x
Ptychospira sexplicata (W. & W.)	?							
Eumetria? sp.	x							
Hustedia circularis (Miller)						x		
Nucleospira obesa Rowley	x							
Rowleyella fabulites (Rowley)						x		
Athyris lamellosa (Leveille)						x		
Cliothyridina tenuilineata (Rowley)	x	x					x	x
Composita sp.		x						
Mollusca								
Conocardium sp. nov		x	x					
Cypricardinia sp.							x	x
Laevidentalium sp.	x							
Lepetopsis sp.	x							
Pleurotomaria sedaliensis Miller			x					
Platyschisma? depressa		cf.						
Euomphalus latus Hall		x	x				x	x
Strophostylus bivolve W. &. W.	x				x			x
Orthonychia sp								x
Orthonychia sp	x		x			x		x
Platyceras nasutus Miller		?						
Platyceras paralius W. & W.							x	
Platyceras obliquus Keyes								x
Platyceras sp.						x		
Arthropoda								
Phillipsia tuberculata M. & W.	x	x						
Griffithides sedaliensis Vogdes	x	x	x		x			

above have been described from higher formations only, but as yet the exact range of the Mississippian fenestelloid species is imperfectly known, and such species might well be represented in the earlier faunas. The presence of such fossils as *Centronelloidea rowleyi*, *Rowleyella fabulites*, *Nucleospira obesa*, and *Ambocoelia levicula*, which are characteristic of the white chert division of the Lower Burlington at Louisiana, Missouri, together with the great assemblage of Lower Burlington forms, would seem to indicate that this was the proper correlation for these faunas.

Bowlder No. 16, Locality 10, has yielded but two forms—*Syringothyris platypleurus* Weller, and *Conocardium* sp. nov. The former is a typical Lower Burlington form, and the latter is identical with forms described from the bowlders referred to the Burlington white chert. While it is not possible to place such a small fauna definitely, such evidence as there is seems to indicate that it should be correlated with the bowlders which have just been described. These faunas, with the exception of the one from bowlder No. 27, were obtained from bowlders of sandstone or quartzite. Bowlder No. 27 was composed of white chert. As a general rule, however, it may be stated that the Burlington faunas are to be looked for in the quartzite bowlders, and the younger and older faunas in the cherts.

A number of other bowlders have yielded faunas which are apparently Lower Burlington in age, but which do not contain a fauna which may be classed as being truly representative. These faunas are listed below:

LOCALITY 10—BOWLDER NO. 1

Platycrinus sp.
Cliothyridina tenuilineata (Rowley)

LOCALITY 10—BOWLDER NO. 6

Productus sp.
Rhipidomella diminutiva Rowley
Terebratuloid shell gen. ? sp. ?
Spirifer biplicoides Weller
Spirifer gregeri Weller?
Spirifer sp.

LOCALITY 12—BOWLDER NO. 19

Fenestella compressa var. *elongata* Cumings?
Brachythyris sp.
Phillipsia tuberculata M. & W.

LOCALITY 7—BOWLDER NO. 21

Spirifer platynotus Weller
Spirifer rowleyi Weller?
Spirifer sp. nov.
Unidentified crinoid

The largest fauna which has thus far been obtained has come from a large chert bowlder which was found by Professor Dake.

This bowlder is so completely weathered that the original texture is entirely gone, and in its place is a porous siliceous mass which powders and crumbles and breaks irregularly. The original bedding of the formation to which this bowlder belonged is well preserved in the specimen and is indicated by a slight lithologic change and a more marked faunal change. Crinoid fragments and pieces of bryozoans are to be found in all parts of the mass, but the former are much more abundant on one side and the latter on the other, and the dividing line is plainly marked. At first an attempt was made to keep the faunas of the two sides separate, but it was soon found that specimens of practically all the species represented were found on both sides of the bowlder. The two faunas are therefore treated as one.

FAUNA OF BOWLDER 102—LOCALITY 1

Coelenterata
- *Amplexus fragilis* White & St. John
- *Monolipora beecheri* Grabau
- Gen. ? sp. ?

Echinodermata
- *Codaster* sp. nov.
- *Platycrinus hemisphericus* M. & W.
- *Platycrinus pratteni* Worthen ?
- *Platycrinus* sp., at least five species, probably more
- *Dichocrinus scitulus* Hall ?
- *Dichocrinus* sp.
- Fragments

Molluscoidea
- *Fenestella cestriensis* Ulr. ?
- *Fenestella cingulata* Ulr.
- *Fenestella compressa* Ulr.
- *Fenestella compressa* var. *elongata* Cumings
- *Fenestella compressa* var. *nododorsalis* Ulr.
- *Fenestella exigua* Ulr. ?
- **Fenestella filistriata* Ulr.
- **Fenestella filistriata* Ulr. ?
- *Fenestella funicula* Ulr.
- *Fenestella limitaris* Ulr.
- *Fenestella multispinosa* Ulr.
- *Fenestella multispinosa* Ulr. ?
- *Fenestella regalis* Ulr.
- *Fenestella rudis* Ulr.

Fenestella tenuissima Cumings
Fenestella triserialis Ulr.
Fenestella triserialis Ulr. ?
Cystodictya lineata Ulr.
**Polypora burlingtonensis* Ulr.
Polypora gracilis Prout
Polypora hallana Prout
Polypora maccoyana Ulr.
Polypora radialis Ulr.
Pinnatopora conferta Ulr.
Hemitrypa perstriata Ulr. ?
Rhombopora dichotoma Ulr. ?
Rhombopora incrassata. Ulr. ?
**Schellwienella burlingtonensis* Weller
**Productus parvulus* Winchell
†*Productus ovatus* Hall
Productus mesalis Hall?
Pustula biseriatus (Hall)
**Rhipidomella diminutiva* Rowley
**Schizophoria subelliptica* (W. & W.)
Tetracamera missouriensis Weller
Rhynchopora beecheri Greger
**Dielasma burlingtonensis* (White)
**Cyrtina burlingtonensis* Rowley
Cyrtina neogenes Hall and Clarke
**Spirifernia solidirostris* White
Spiriferina norwoodana (Hall)
Delthyris similis Weller
Spirifer rostellatus Hall
Spirifer logani Hall
Spirifer tenuimarginatus Hall ?
Spirifer tenuicostatus Hall
†*Brachythyris suborbicularis* Hall
Pseudosyrinx keokuk Weller
Reticularia pseudolineata (Hall)
Eumetria verneuiliana Hall
**Nucleospira obesa* Rowley
**Cliothyridina incrassata* (Hall)
Cliothridina parvirostris (M. & W.)

Mollusca

Cypricardinia sp.
Orthonychia pabulocrinus (Owen)
Platyceras obliquus (Keyes)
Platyceras equilateralis Hall
Undetermined forms

Arthropoda

**Phillipsia tuberculata* M. & W.

Griffithides sedaliensis Vogdes

A careful comparison of this fauna with the extensive collection in the Walker Museum, from the Keokuk and Warsaw formations from a number of localities in the Mississippi Valley, has indicated the approximate age of the fauna, but does not allow it to be placed exactly. Its affinities are with the Upper Keokuk and Lower Warsaw. What little evidence there is seems to favor the placing of this bowlder in the Lower Warsaw.

Spiriferina norwoodana, *Pustula biseriatus*, *Delthyris similis*, *Fenestella exigua*, *F. funicula*, *F. compressa* var. *nododorsalis*, *Polypora gracilis*, and *Pinnatopora conferta* occur in the Lower Warsaw at a number of localities. *Eumetria verneuiliana*, *Pseudosyrinx keokuk*, and *Monolipora beecheri*, while found in both formations, appear to be more abundant in the Lower Warsaw. On the other hand, *Fenestella rudis*, *F. regalis*, *Polypora hallana*, and *P. maccoyana* have heretofore been identified from the Keokuk only. *Spirifer rostellatus* is well known in the Keokuk, but its presence in the Warsaw has been regarded as doubtful.

An interesting recurrent Burlington association appears in this bowlder, the species of which are indicated in the faunal list by an asterisk. A few other species which are common to many Mississippian formations are indicated by the dagger. This recurrent element corresponds almost exactly to the faunas assigned to the Burlington white chert. It is known at the present time that such a recurrent group of species does occur either in the top of the Keokuk formation or in the base of the Warsaw, in southeastern Missouri, and this bowlder was undoubtedly from this horizon originally.

Closely related to the fauna just described are the three faunas listed below:

BOWLDER 13—LOCALITY 10

Archimedes owenanus Hall

MISSOURI BUREAU OF GEOLOGY AND MINES, COLLECTION NO. 4, LOCALITY 12

Archimedes grandis Ulrich

Orthotetes keokuk (Hall)

Productus ovatus Hall

BOWLDER 34—LOCALITY 6

Fenestella rudis Ulrich?
Archimedes grandis Ulrich
Productus ovatus Hall
Productus setigerus Hall
Rhynchopora beecheri Greger
Pseudosyrinx keokuk Weller
Camarophoria? sp.

The exact correlation of these faunas is a difficult matter, since nearly all of the species represented are common to both the Keokuk and the Lower Warsaw. *Archimedes owenanus* is a common Keokuk form, but it also appears in the Lower Warsaw. *A. grandis* is less common, but its stratigraphic range is believed to be about the same as that of *A. owenanus*. *A. wortheni*, which is so characteristic of the Warsaw faunas, has not been found. These faunas are probably best classed as Keokuk. No trace of the recurrent fauna mentioned on page 573, has been found in any of them.

MISSOURI BUREAU OF GEOLOGY AND MINES, COLLECTION NO. 5

Fenestella serratula Ulrich
Fenestella serratula var.
Fenestella serratula Ulrich?
Fenestella exigua Ulrich
Fenestella cf. *exigua* Ulrich
Fenestella exigua Ulrich?
Fenestella sp. (3)
Polypora varsoviensis Prout
Polypora striata Cumings
Polypora spininodata Ulrich
Cystodictya lineata Ulrich
Hemitrypa sp.
Schizophoria sp.
Cypricardinia sp.

This is apparently the youngest fauna which has been found thus far. It is characterized by *Polypora varsoviensis*, the large forms of which are found in great abundance in almost every fragment. This species is common in the Warsaw and younger beds. The specimens referred to *Cypricardina* sp. do not appear to belong to the same species as the ones found in bowlder No. 102,

but are closely related. This fauna is probably Warsaw, but, in the absence of detailed faunal studies of the Warsaw, a more exact correlation cannot be made.

Briefly summarized, the results of this study show that the faunas obtained from these residual bowlders are much more diverse than has previously been supposed. They indicate a partial submergence, in early Mississippian time, of a considerable portion of the northern end of the Ozark uplift. From the study of so small an area, not much is to be inferred as to the movements and distribution of the Mississippian seas during the time when the formations represented in these bowlders were deposited.

Typical Chouteau faunas and pre-Chouteau faunas are conspicuously absent, though farther north the Chouteau formation is represented by small outliers and scattered patches of bowlders. From this it would seem as if the sea did not cover this part of the uplift during Kinderhook time, but that a gradual submergence during the late Kinderhook allowed the Burlington seas to invade this area. This supposition is further strengthened by the sandy character of many of the bowlders, which suggests that the ancient shore line was not far distant. An alternative view is that the Kinderhook formations, or part of them, were present, and, not being as resistant as the younger formations, have entirely disappeared. However, if this is the case, why should the Chouteau formations occur as bowlder deposits in the counties between this area and the Missouri River? On the whole, the evidence seems to favor the first hypothesis.

Not much evidence of the Upper Burlington with its typical crinoid fauna has yet been found, but some specimens in the original School of Mines collection suggest that it was represented. In most places where it is exposed at present it contains much less chert than does the Lower Burlington, and this fact may account for its failure to be more commonly preserved. The Keokuk and the Lower Warsaw are probably both represented, but so great is the similarity between their faunas that the few collections which have been obtained do not suffice to make the distinctions clear. Up to the present time, no evidence has been obtained of any faunas younger than the Lower Warsaw.

EVIDENCE BEARING ON A POSSIBLE NORTHEASTWARD EXTENSION OF MISSISSIPPIAN SEAS IN ILLINOIS

W. W. DAVIS
University of Chicago

CONTENTS

Introduction.—For some time it has been known that fossils of Mississippian age can be collected within the city limits of Chicago. These Mississippian fossils, which occur in bowlders in the glacial drift, were brought to notice by Mr. William Johnston, who reported them to Professor Weller in 1915. The collections which form the basis of the present report are in part those first secured by Mr. Johnston; others have been collected by Professor Weller, and still others by the writer.

Location of the bowlders.—The drift bowlders which have afforded the fossils occur in the southeastern portion of the clay-pit of the Carey Brick Company, located near the northeastern corner of Grand Avenue and New England Avenue, in the northwestern portion of the city, between Hanson Park and Montclare, being closer to the latter place. The clay-pit is excavated in a terminal moraine, which belongs either to the lake border or to the Valparaiso morainic system, but probably to the former.[1] The morainic

[1] *Areal Geology Sheet*, Chicago Folio.

material contains a considerable number of glacial bowlders of various types and sizes. Some of them are of igneous origin, others carry fossils of Niagaran age. Those containing the Mississippian fauna were observed only in the southeastern part of the pit. The bowlders have been piled into many small heaps by the workmen, several of which are made up almost exclusively of those of Mississippian age. The collections which have been made were largely secured from these piles, but similar bowlders may be found scattered over the southeastern part of the floor of the pit.

Lithologic character of the bowlders.—In their lithologic character these Mississippian bowlders are dolomitic limestones, which closely resemble the Niagaran dolomite of the Chicago region in general appearance; when fresh they are bluish gray in color and very hard, but on weathering they take on an earthy, yellowish-brown color and become very soft.

Physical condition of the bowlders.—The great majority of the bowlders have well-weathered surfaces, and in many examples the outer surface to the depth of an inch or more is decomposed to a soft, yellowish, more or less porous rock as a result of weathering. Some large pieces are completely weathered to the center. This weathered condition of the Mississippian bowlders is, in general, in marked contrast to that of the bowlders of other ages found in the pit. Many of the Mississippian bowlders are rather angular, and none have well-worn faces; they vary in size from small fragments up to irregular blocks containing two or more cubic feet; in general, they lack the characteristic appearance of typical glacial bowlders. If their location were not known, they might easily be mistaken for residual fragments of weathering.

So far as now known, these bowlders are confined to the southeastern section of the Carey clay-pit. A few small masses with the same lithological character were found on the surface of the moraine near the pit, but as none of these fragments have afforded determinable fossils they cannot be identified with certainty.

Criteria by which the bowlders may be recognized.—The Mississippian drift bowlders commonly may be recognized by their dirty, yellowish, weathered surfaces and by their two most marked paleontological characteristics, namely, (*a*) an abundance of

crinoidal remains, mostly stems, and (*b*) the presence of numerous specimens of *Spirifer* with plicated fold and sinus.

The fauna of the bowlders.—These bowlders are abundantly fossiliferous, but the fossils are largely fragmentary and are commonly poorly preserved. Unfortunately they are nearly all in the form of molds, a condition of preservation which has added to the difficulties of their identification. None of the fossils are silicified, but a few of the cavities left by the solution of the shells are sprinkled with crystals of pyrite and dolomite. The extremely weathered portion of the rock is generally too soft to yield determinable fossils, and the unweathered portions yield comparatively few. The great majority of the better specimens have been collected from the partially weathered portions.

The most abundant fossils are the crinoids, although most of the specimens are mere fragments of stems, few of which can be identified even generically, and they are of little scientific value except to show that the rock has been a conspicuously crinoidal limestone. Next to the crinoids the brachiopods are the most common fossils, and owing to their abundance and better state of preservation they form the most satisfactory element of the whole fauna. Besides the crinoids and the brachiopods the fauna contains corals, blastoids, bryozoans, pelecypods, and gastropods, none of which are represented by numerous species or specimens.

The composition of the fauna is shown by the accompanying list of species that have been identified (Table I). The number of examples of each species that has been observed is recorded after each name for the purpose of showing the relative importance of the several members of the fauna; the geologic range and geographic distribution are shown in the several columns.

The geographic and geologic relationships of the fauna.—The geographic and geologic relationships of this fauna are not difficult to determine. Considering first the brachiopods, the list shows that all the forms are found in the Mississippi Valley, although a few species have a wider range. Of these brachiopods, two species, *Spirifer gregeri* and *Spirifer mundulus*, are Lower Burlington. Three species, *Dielasma burlingtonensis*, *Spirifer forbesi*, and *Spiriferella plena*, are confined to the Burlington. Seven species,

LIST OF THE MONTCLARE MISSISSIPPIAN FOSSILS

Name	Number	Geologic Range				Geographic Distribution			
		Pierson	Fern Glen	Burlington	Keokuk	Iowa	Illinois	Missouri	Other Localities
Corals (unidentifiable),	10								
Crinoidea (exclusive of stems)									
Dizygocrinus rotundus? Shumard	1			*		*	*	*	
Dorycrinus unicornis Owen & Shumard	1			*		*		*	New Mexico
Platycrinus sp.	2	*	*	*		*	*	*	
Unidentifiable fragments	15								
Blastoidea									
Cryptoblastus melo Owen & Shumard	3			*		*	*	*	
Bryozoa									
Fenestelloid fragment									
Brachiopoda									
Athyris lamellosa Leveille	2	*	*	*	*	*	*	*	Indiana, Kentucky, Ohio, New Mexico, Nevada, Wyoming, Europe
Brachythyris suborbicularis Hall	8			*	*	*	*	*	Indiana
Chonetes multicostus Winchell	2		*	*		*		*	Tennessee
Cliothyridina prouti Swallow	1		*			*	*	*	New Mexico
Cyrtia? inexpectans? Weller	1				*			*	
Dielasma burlingtonensis? White	2			*		*		*	Nevada
Leptaena analoga Phillips	1	*	*	*		*	*	*	Ohio, New Mexico, Nevada, Utah, Wyoming, Nova Scotia
Productus fernglenensis Weller	10	*	*					*	
Pseudosyrinx sp.?	2	*	*	*	*	*	*	*	
Ptychospira sexplicata White & Whitfield	1		*			*	*	*	
Rhipidomella burlingtonensis Hall	32	*		*		*	*	*	Utah?
Schizophoria swallovi Hall	16	*		*		*	*	*	
Spirifer forbesi Norwood & Pratten	1			*		*	*	*	
Spirifer gregeri Weller	16			*				*	
Spirifer mundulus Rowley	1			*				*	
Spirifer shepardi Weller	104	*						*	
Spiriferella neglecta? Hall	1				*	*	*	*	
Spiriferella plena Hall	1			*		*	*	*	
Syringothyris sp.?	2		*	*	*	*	*	*	
Pelecypoda									
Aviculopectan sp.?	1			*		*	*	*	
Conocardium sp.?	1			*		*	*	*	
Gastropoda									
Euomphalus latus Hall	6			*		*	*	*	Ohio
Platyceras obliquus? Keyes	1			*		*		*	
Platyceras paralius? White & Whitfield	1		*	*		*		*	Ohio

For range and distribution see *U.S.G.S. Bulletin 153; Illinois State Geological Survey, Monograph I;* Walker Museum Collection.

Athyris lamellosa, *Brachythyris suborbicularis*, *Leptaena analoga*, *Ptychospira sexplicata*, *Rhipidomella burlingtonensis*, *Schizophoria swallovi*, and *Chonetes multicostus*, are not limited to the Burlington; but the Lower Burlington seems to be the upper limit of *Chonetes multicostus*, *Leptaena analoga*, and *Ptychospira sexplicata*, while *Rhipidomella burlingtonensis* and *Schizophoria swallovi* are not found above the Burlington. Two species, *Cliothyridina prouti* and *Productus fernglenensis*, are found typically in the Fern Glen, and one species, *Spirifer shephardi*, is typical of the Pierson limestone of southwestern Missouri, which may be the equivalent of the Fern Glen. The Fern Glen commonly has been classed as uppermost Kinderhook, but it is altogether probable that it should rather be considered as lowermost Osage. Species of the two genera *Pseudosyrinx* and *Syringothyris* are found in the Burlington. One species, *Cyrtia inexpectans*, which is very rare, has been described from residual chert in Missouri, supposed to be of Keokuk age, and another species, *Spiriferella neglecta*, is found in the Keokuk, but these two species are the least certainly identified of any of those recorded.

The brachiopods of the foregoing list are clearly related to those of the early Osage faunas of the Mississippi Valley, as these faunas are developed in Iowa, Illinois, and Missouri, and the formation from which they have originated may be certainly correlated as not younger than the Burlington limestone, and in all probability as Lower Burlington.

The other elements of the fauna confirm the correlation suggested by the brachiopods. The abundance of crinoidal remains immediately suggests the Burlington limestone. Both *Dizygocrinus rotundus* and *Dorycrinus unicornis* are typical Burlington crinoids. *Platycrinus* is also found in the Burlington, though it is not confined to that formation. The blastoid *Cryptoblastus melo* is another member of the Burlington fauna and is quite limited in its geologic range. The gastropod *Euomphalus latus* is another characteristic Burlington species, and both species of *Platyceras* recorded are reported from the Burlington limestone. The corals, bryozoans, and pelecypods which have been recorded have not been specifically identified, but all the genera recognized are known to be present in the Burlington.

The place of origin of the bowlders.—As Montclare is 165 miles in a northeasterly direction from the nearest known Mississippian outcrop in the Mississippi Valley, the question at once arises: From where were these Mississippian bowlders transported by the glaciers? The general direction of ice movement in the Chicago region during the last glacial epoch was somewhat west of south, the published records of the directions of glacial striae west of the city showing directions varying from S. 57° W. to due west.[1]

Considering the known direction of glacial ice movement, the first inference is that the bowlders may have been transported from the known Mississippian outcrops in Michigan, but a careful consideration of the Mississippian formations of that state and of their faunas makes such an origin highly improbable.

The Mississippian section of Michigan as given by Lane[2] has been followed by all later writers.

In this section the following subdivisions are recognized:

Bayport or Maxville limestone: Light and bluish cherty limestones and calcareous sandstones.

Michigan series: Dark or bluish limestones and dolomites, with gypsum and blue or black shales; some reddish or greenish shales and dark or red sandstones.

Marshall sandstone: White and red sandstone, often pyritic, peanut conglomerates, sandy shales, whetstones, and red shales.

Coldwater series: Blue shales with nodules of iron carbonate, sandstone, subordinate streaks of fine-grained limestone, black shale at the base.

Berea sandstone: White sandstone, nowhere exposed in the state.

The published list of fossils from these Michigan formations[3] shows them to be faunally related to the Mississippian of Ohio rather than to the Mississippi Valley formations. Writers are not altogether in accordance regarding the correlation of these formations, but, giving the widest possible latitude, the Montclare bowlders must have been derived from a formation whose age was

[1] *Chicago Geological Folio*, pp. 506.

[2] *Annual Report, Geological Survey of Michigan*, 1908, pp. 74–86. (1909.)

[3] *Geological Survey of Michigan*, Vol. VII, Part II, pp. 253–70.

included within the time of deposition of the Coldwater, Marshall, and Michigan formations of Michigan. The published faunal lists from all these formations are made up largely of pelecypods, and from all the available lists a single species, *Spirifer forbesi* (and this identification is admitted to be very questionable), is recorded from the Michigan series, which has been identified in the Montclare collection. Even if the identification of this species from Michigan is correct, it is still quite evident that the Montclare bowlder fauna has no relationships with the Michigan Mississippian which are worthy of consideration. Furthermore, the lithologic character of the Montclare bowlders is totally different from that of any of the Michigan formations.

From the foregoing consideration of the faunal and lithologic characteristics of the Mississippian formations of Michigan it may be assumed as a demonstrated fact that the Montclare bowlders were not transported from across Lake Michigan to their present resting-place.

The only alternative conclusion in regard to the source of these bowlders is that they were originally in place at no great distance from where they now lie. Such a conclusion is further confirmed by the physical condition of the bowlders themselves. They are angular in outline and exhibit much less wear than most of the associated bowlders. The present weathered condition of the bowlders is probably original weathering accomplished before they were moved by the glacier. This is suggested by the different degrees of weathering of the bowlders themselves and by the different surfaces of the same bowlders. Furthermore, the other bowlders of similar composition which were buried with the Mississippian bowlders in the glacial débris are still essentially unweathered, even upon their surfaces.

Conclusions.—A study of these Montclare glacial bowlders of Mississippian age seems to establish the following important conclusions:

1. There existed, previous to the last glacial advance, an outlier of Mississippian rocks in northeastern Illinois, probably resting on limestone of Silurian age. The remnants of such an outlier may well be in existence, completely buried at the present time by

glacial drift. The actual position of this outlier cannot now be determined, but it was at no great distance from the present position of the bowlders and may well have been within the present limits of Chicago.

2. The limestone comprising this Mississippian outlier contained a prolific fauna of brachiopods, crinoids, and other forms of life, every species of which, so far as they have been certainly identified, is present also in the rocks of lower Osage age in the Mississippi Valley. The whole association of species suggests a very definite correlation of these Mississippian rocks with the Lower Burlington limestone of western Illinois, Iowa, and Missouri. There is no suggestion whatever of any faunal connection with the Mississippian formations of Michigan.

3. On the basis of the two foregoing conclusions, the extension into northeastern Illinois of the Mississippian sea, which occupied the Mississippi Valley region in early Osage time, may be assumed.

"SOME EFFECTS OF CAPILLARITY ON OIL ACCUMULATION" BY A. W. McCOY[1]

DISCUSSION BY

C. W. WASHBURNE
New York

Students of petroleum are indebted to Mr. McCoy for the three useful experiments in this paper. His first conclusion is that oil may accumulate in the larger pores and other spaces of rock, regardless of structure. This fact had been recorded previously in the occurrence of oil in lenticular sands, and I had shown its theoretical necessity.[2] The additional experimental evidence is most welcome. The main argument of the paper is an attempt to show that capillary action possibly may lift the strata into anticlines. This idea appears impossible for four reasons.

First, the pressures created by capillarity are exerted by fluids in open spaces which communicate, more or less deviously, with the ground surface. The perfection of this communication through shale is of the same order as the perfection of transmission of the capillary pressures (assuming that these exist) that are transmitted through shale into sandstone. Moreover, any pressures in the fluids in sandstones are exerted through all spaces, laterally as well as vertically, and would be so equalized through the entire bed of sand that only a local hydraulic gradient would be left to deform the sand. That such slight difference of pressure is unable to tilt a sand need not be argued. Even if the capillary pressures could deform a sand, they would not disturb lower sands along the same axis or lift any of the underlying strata.

Secondly, the amount of pressure available under Mr. McCoy's assumed conditions (p. 802) would not be "the difference in the

[1] *Jour. Geol.*, XXIV (1916), 798–805.

[2] C. W. Washburne, *Transactions A.I.M.E.*, L, 831.

capillary pressures of oil and water for that size of opening." It would be only (*a*) the pressure exerted by the water-oil surfaces beneath the oil, less (*b*) the pressure of the oil-gas surfaces on the hemiglobules of oil that are being forced out of the small capillaries into larger spaces. Since (*a*) and (*b*) are of similar magnitude, their difference, amounting only to a fraction of an atmosphere, cannot be considered a cause of rock deformation.

In other words, Mr. McCoy takes a wrong basis for his calculation of capillary deforming force, and this nullifies the calculation at the end of his paper.

Thirdly, the amount of capillary pressure exerted in a group of tubes of variable size and having many lateral connections, as in rock, cannot exceed the pressure in the largest of these tubes plus the head required for an adjusting flow of gas or liquid through the lateral connections from the finer to the larger pores. If shale is cut by minute open joints or fissures, the low capillary pressures in the latter must limit the effective capillary pressure per square inch in all connecting pores.

Pores that are completely closed above the point of the highest liquid-gas surface within them would feel the complete pressure produced by that surface. Capillary action in completely inclosed pores would not contribute to the general pressure or affect the problem under discussion. In all connected pores, the general capillary pressure could not rise appreciably above the minimum capillary pressure, determined in the largest pores or joints.

I believe that the second and third arguments reduce the probable effective capillary pressure, under the conditions of Mr. McCoy's problem, to a maximum of one or two atmospheres, if the rock is cut by any minute open joints or large pores. Certainly the pressure of 200 atmospheres, which he deduces, is out of the question as a general capillary pressure in rock.

Fourthly, there is no definite orientation to capillary pressures in rock-pores. They push and pull every way and tend to balance each other. The ideal distribution of water, gas, and oil assumed by Mr. McCoy would cause a small capillary pressure of definite

orientation, but the assumed distribution is improbable. The probable original distribution is a sand filled mostly with water and imbedded in shale the pores of which are filled with water, oil, and gas, without any regularity or order.

The three useful experiments so carefully described by Mr. McCoy are worthy of careful study by students of oil, and I trust that we may have more experiments from the same author.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

BOWEN, N. L. "The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Amer. Jour. Sci.*, XL (1915), 161–85.

The terms haplobasaltic, haplodioritic, and so on, are applied by the writer to simple (pure) artificial mixtures of feldspars of various compositions, and diopside. He uses the rock names according to the best and most recent practice. Various mixtures of these substances were studied by the quenching method of thermal analysis, that is, by sudden chilling at known temperatures, and the material was studied microscopically. No attempts were made to study the optical properties of the minerals formed, it being necessary only to distinguish diopside from plagioclase in these experiments, the results of which are plotted in numerous diagrams. From his results the writer concluded that crystallization controls differentiation in the subalkaline igneous rocks.

BOWEN, N. L., and ANDERSEN, OLAF. "The Binary System MgO-SiO_2," *Amer. Jour. Sci.*, XXXVII (1914), 487–500.

A study of equilibrium in the binary system MgO-SiO_2 by the method of quenching. Forsterite (Mg_2SiO_4) and clinoenstatite ($MgSiO_3$) were found capable of existing in contact with liquid in the binary system. Clinoenstatite was the only stable form of $MgSiO_3$ found. It has no true melting-point, but at 1,557° breaks up into forsterite and liquid. At 1,577° the forsterite dissolves. There is no eutectic between these two compounds.

BOWEN, N. L. "The Ternary System Diopside-Forsterite-Silica," *Amer. Jour. Sci.*, XXXVIII (1914), 207–64.

An investigation of various mixtures of silica, calcium carbonate, and magnesia. It was found that the systems diopside-silica and diopside-forsterite show the simple eutectic relations; forsterite-silica shows one intermediate compound (clinoenstatite) unstable at its melting-point; and clinoenstatite-diopside forms an unbroken series of solid

solutions, corresponding to the monoclinic pyroxenes. The triangular diagram, therefore, shows only three boundary curves and one ternary invariant point. The writer shows that crystallization may proceed according to two different methods, and the importance of distinguishing between them is discussed. The optical properties of the pyroxenes are discussed at some length; extinction angles, refractive indices, and optic axial angles are measured and the orientation is determined.

BOWEN, N. L. "Crystallization-Differentiation in Silicate Liquids," *Amer. Jour. Sci.*, XXXIX (1915), 175–91.

Laboratory experiments showed that olivine and pyroxene crystals sink and tridymite floats in artificial melts of diopside, forsterite, and silica. From the rate of sinking, the viscosities of the melts were found to increase with increase in silica.

COLLINGBRIDGE, HARVEY. "The Determination of the Maximum Extinction Angle, Optic Axial Angle, and Birefringence in Twinned Crystals of Monoclinic Pyroxenes in Thin Section by the Becke Method," *Mineralog. Mag.*, XVII (1914), 147–49.

Gives a method for determining various optic properties by observations on twinned crystals which show the emergence of an optic axis in one portion.

COLLINS, W. H. *The Huronian Formations of Timiskaming Region, Canada.* Museum Bull. No. VIII, Geol. Surv., Dept. Mines, Canada. Ottawa, 1914. Pp. 27, figs. 3, pls. 1.

CROSS, WHITMAN. *Lavas of Hawaii and Their Relations.* U.S. Geol. Surv., Prof. Paper 88, Washington, 1915. Pp. 97, map 1, pls. 2, fig. 1, bibliography.

The writer describes, with considerable space devoted to the norms, various olivine-bearing and olivine-free-, bronzite-, picrolitic-, nephelite-, and melilite-nephelite-basalts, limburgites, soda-trachytes, trachyandesites, a kauaiite or oligoclase-augite-diorite, some basalt tuffs, and a

gabbro. Forty-three chemical analyses are given, and in most cases the normative minerals are computed. In the general discussion the characteristics, chemical compositions, normative compositions, the relations of norms to modes, and the classification are considered. Twenty-two pages are devoted to the distribution of the rocks in the Hawaiian Islands and of analogous rocks elsewhere in the world. The writer discusses the Atlantic and Pacific provinces, and the alkalic and calcic series (alkali and alkali-lime series of Rosenbusch), and concludes with a discussion of differentiation in the Hawaiian magmas.

CROSS, WHITMAN. "On Certain Points in Petrographic Classification," *Amer. Jour. Sci.*, XXXIX (1915), 657–61.

An answer to several criticisms of the C.I.P.W. system of rock classification.

DALMER, K. *Erläuterungen zur geologischen Spezialkarte des Königreichs Sachsen.* Sektion Treuen-Herlasgrün, Blatt 134. 2d ed. revised by E. Weise and A. Uhlemann. Leipzig, 1913. Pp. 58, pl. 1.

Picrite, diabase, granite, quartz-porphyry, mica-porphyrite, various contact metamorphosed schists, and sediments are described.

DALY, REGINALD A. *Origin of the Iron Ores at Kiruna.* Vetensk. och Prakt. Undersök. i Lappland. Stockholm, 1915. Pp. 35, figs. 4.

Expresses the view that the "inclusions" of ore in the Kiruna quartz-porphyry, are endogenous, and represent "frozen-in" units of differentiation. The accumulation of such ore-masses by gravity is thought to be the cause for the origin of the main ore bodies.

DALY, REGINALD A. *Geology of the North American Cordillera at the Forty-Ninth Parallel.* Mem. 38, Dept. Mines. Ottawa, 1912. Pp. 840, maps 17, pls. 73, figs. 42.

Although the date on the title-page of this important memoir is 1912, and the date of transmission 1910, it was not distributed until 1914. In the meantime Daly's *Igneous Rocks and Their Origin,* which contains a much fuller statement of the theories expressed in chaps.

xxiv to xxviii, appeared. It is almost impossible in the space available here, to abstract a book of this character. The Table of Contents alone covers 15 pages, and a synopsis given by the author 8 pages.

After describing the area covered, the author shows the various subdivisions into which the Cordilleras have been divided, and suggests various additions and changes. Then follow descriptions of the stratigraphy and structure of the Clarke, MacDonald, Galton, Purcell, and Selkirk mountain systems, and the Rossland, Christina, Midway, Okanagan, Hozomeen, Skagit, and other ranges. In chaps. ix to x the Purcell lava and associated intrusives are described. The differentiation in the Moyie sill is ascribed to the assimilation of quartzites, and the writer offers proof of this as well as of gravitative differentiation. A great number of chemical analyses are presented. The descriptions of the rocks are given in a manner which might well be followed by other petrologists, namely that of giving the mode of the rock as well as the norm. Further, it is advisable, as is here done, to indicate whether the mode was determined by the Rosiwal method, or by recalculation of the analysis and comparison with the thin section. Pages 677 to 791 are mostly theoretical, and deal with the theory of igneous rocks, classification of igneous bodies, mechanics of batholithic intrusion, differentiation, classification of magmas, etc.

The report is unusually interesting, not only in the theoretical part, but also in the descriptive portions, which in most geologic reports have a soporiferous effect.

DALY, REGINALD A. "Problems of the Pacific Islands," *Amer. Jour. Sci.*, XLI (1916), 153–86, pl. 1, figs. 38.

A plea, given at the meeting of the American Association for the Advancement of Science at San Francisco last August, for the establishment of a central bureau for the comprehensive exploration, from a scientific standpoint, of the Pacific Islands. It is estimated that the cost of such a project will be from $800,000 to $3,000,000, depending upon the thoroughness of the work, and that it will require about ten years of time for the field work, and an additional five or ten years for systematizing and publishing the results. The writer presents a number of the problems which should be solved.

DRYSDALE, CHARLES W. *Geology of Franklin Mining Camp, British Columbia.* Mem. 56, Geol. Surv., Dept. Mines. Ottawa, 1915. Pp. 246, pls. 23, figs. 16, bibliography.

A report on a mining camp in the Yale District in south-central British Columbia. The Franklin group contains the oldest rocks in the district, consisting of metamorphic tuffs, quartzites, and argillites, the latter carrying Paleozoic fossils. The rocks may represent early marine coastal conditions of sedimentation and igneous activity prior to the submergence and eastward transgression of a Carboniferous sea. At the close of the Paleozoic the main folding and metamorphism of the region took place, and the Franklin District thereafter remained above the sea. During the Jurassic period there came the intrusion of a granodiorite batholith beneath a considerable cover of sediments. It did not reach the surface. The Cretaceous period was one of long-continued denudation, laying bare great thicknesses of Paleozoic rocks and even exposing the underlying Jurassic batholith in places. At the close of the Mesozoic the whole Cordillera was uplifted and the Valhalla granite was probably intruded. The early Tertiary was a period of regional sinking accompanied by some volcanic activity. It closed with the tilting of the Kettle River formation, and a new cycle of erosion started. At this time also there came the intrusion of monzonite. During the Miocene there came intrusions of syenite, followed by pyroxenite and augite-syenite, pulaskite-like dikes, and trachyte flows. Regional uplift closed the Tertiary. During the Pleistocene all except a few of the highest peaks of the Cariboo Range were covered by the Cordilleran ice sheet.

A number of chemical analyses of the igneous rocks are given.

ESKOLA, PENTTI. *On the Petrology of the Orijärvi Region in Southwestern Finland.* Bull. com. géol. Finlande, No. 40. Helsingfors, 1914. Pp. 277, pls. 6, maps 2, figs. 55, bibliography.

This interesting bulletin gives an account of the petrology of a series of Archean metamorphic rocks in the vicinity of Orijärvi. After a short geologic history of the region, the author gives careful and detailed petrographic descriptions of various granites, magmatites, pegmatites, diorites, gabbros, hornblendites, aplites, peridotites, amphibolites, leptites, and limestones. He then describes the exogenic contact-zones of the oligoclase-granite, and gives petrographic determinations of the

cordierite-anthophyllite, quartz-cordierite-, cordierite-, and andalusite-quartz-mica-rocks, cordierite-gneiss, plagioclase-biotite-gneiss, cummingtonite-amphibolite, and the skarn rocks. A great many chemical analyses are given, and they are recomputed into the norm as well as into Osann's system. Further, all analyzed rocks whose mode could be determined under the microscope have been recomputed into the mode, an example which might well be followed by petrographers in this country.

FENNER, CLARENCE N. "The Stability Relations of the Silica Minerals," *Amer. Jour Sci.*, XXXVI (1913), 331–84.

The following inversion-points were determined at atmospheric pressure.

$870^\circ \pm 10^\circ$ quartz $\leftrightarrows$ tridymite
$1470^\circ \pm 10^\circ$ tridymite $\leftrightarrows$ cristobalite

Velocity of transformation very slow.

α-quartz $\rightarrow$ β-quartz 575°
β-quartz $\rightarrow$ α-quartz 570°
α-tridymite $\rightarrow$ β_1-tridymite 117°
β_1-tridymite $\rightarrow$ β_2-tridymite 163°
α-cristobalite $\rightarrow$ β-cristobalite 274° to 220°, depending upon the previous heat treatment.
β-cristobalite $\rightarrow$ α-cristobalite 240° to 198°, depending upon the previous heat treatment.

The transformation in the last six cases takes place promptly.

The melting-point of cristobalite is *ca.* $1,625^\circ$, while quartz is at least 155° lower.

FERMOR, L. LEIGH. "Preliminary Note on Garnet as a Geological Barometer and on an Infra-Plutonic Zone in the Earth's Crust," *Records Geol. Surv., India*, XLIII (1913), 41–47.

A comparison of the specific gravities of certain garnet-bearing rocks with the specific gravities of the same magmas crystallizing in normal minerals showed that the garnet-bearing rocks occupied from 10 to 20 per cent less room. From this the author concludes that garnet-bearing rocks, such as kodurite, eclogite, etc., are high-pressure forms of normal rocks. He therefore postulates the existence, below normal plutonic rocks, of a shell characterized by garnets wherever a sesqui-oxide radicle exists. For this shell he proposes the term "infra-plutonic." Another

mineral of this zone is diamond. Under normal conditions the author thinks a relief of pressure would liquify a certain portion of the infra-plutonic rocks which, on being intruded into the higher zones of the earth's crust, would there solidify under less pressure as a normal plutonic rock. Only under exceptional circumstances, for example when the isogeotherms are lowered more rapidly than the pressure, will the garnet-rock cool in its infra-plutonic form, to appear later by erosion. The author considers this garnet-shell to be continuous around the earth and potentially liquid, subject to local fusion and the formation of reservoirs wherever there is a reduction of superincumbent pressure.

Applying this theory to meteorites, he thinks the chondrules, which occur in so many stony varieties, were formerly garnets, and that cliftonite in the iron meteorites was formerly diamond.

FETTKE, CHARLES REINHARD. "The Manhattan Schist of Southeastern New York State and Its Associated Igneous Rocks," *Ann. N.Y. Acad. Sci.*, XXIII (1914), 193–260, pls. 8, bibliography.

The Manhattan schist, the youngest of the three crystalline metamorphic formations which form bed-rock in southeastern New York, occurs in a series of closely folded anticlines and synclines, usually unsymmetrical and in many cases overturned toward the west. The axes of the folds run northeast and southwest and gently dip to the south. The chemical composition and field-relations of the schist show that it is of sedimentary origin, derived from shales, sandstones, and arkoses. These were laid down conformably upon the underlying limestone to a depth of several thousand feet. Later a series of basic rocks—hornblende- and actinolite-schists of dioritic and gabbroic characteristics, and granodiorite-gneiss (better gneissoid-granodiorite, since it was determined to be of igneous origin)—was intruded in the form of sheets and sills. Now came a period of intense folding accompanied by intrusions of granite, aplite, and pegmatite. Later there were intruded various basic rocks—norites and pyroxenites of the Cortlandt series, hornblendite near Croton Falls, and other rocks now altered to serpentine. The pegmatitic intrusions still continued, for these later basic rocks are cut by them in several places.

Reviews

The Origin of the Magmatic Sulfid Ores. By C. F. Tolman, Jr. and Austin F. Rogers. Leland Stanford Junior University Publications, 1916. Pp. 76, figs. 7, pls. 20.

After reviewing the literature bearing on the modes of origin of the various magmatic ore deposits, the authors have proposed as their thesis that "the magmatic ores have in general been introduced at a late magmatic stage as a result of mineralizers and that the ore minerals replace the silicates. This replacement, however, differs from that caused by destructive pneumatolytic or hydrothermal processes in that quartz and secondary silicates are not formed at the time the ores are deposited."

The authors follow the position taken by Bowen in his recent work establishing the process of fractional crystallization as the dominant one during magmatic differentiation. After studying suites of specimens from Sudbury, Ontario, Elkhorn, Montana, Ookiep, South Africa, and Plumas County, California, the conclusion is reached that the ores have been introduced by pneumatolytic means after the formation of the rock-bearing silicates. The authors show clearly that the sulphides are a late magmatic product, that they surround the silicates, cut them with well-defined veinlets, embay them, and penetrate cleavage cracks and contacts with other minerals. The absence of metallic silicates makes it clear that the ores were not introduced as molten material, while the replacement of early formed minerals indicates the presence of mineralizing solutions. The complete absence of reaction rims shows that the replaced material was removed by the same agents which introduced the ores. Selective replacement is shown by the preservation of the original graphic texture of the rocks in the ores. There is also evidence of the alteration of pyroxene to hornblende prior to the introduction of the ore minerals, suggesting the presence of aqueous vapor. The small amounts of hydrothermal alteration present appear to be related to a post-magmatic stage.

The authors conclude that the temperatures involved in the deposition of the ores did not exceed 300 C. to 400 C., but it is unsatisfactory so to limit the temperature without further data than are here presented.

That the temperatures were higher than those of pegmatites is admitted by the writers, but the only thing certain about the temperatures of the pegmatites is that some minerals in some pegmatites formed at temperatures lower than 575° C. The dominance of pyrrhotite as compared with pyrite is recognized, and this indicates a high temperature, since pyrite is less stable than pyrrhotite at such temperatures.

The paper represents an excellent piece of work and is a distinct contribution to the knowledge of magmatic processes. It also serves to emphasize the fact that a great deal must be known concerning the minute textures of rock masses, other than that they are merely in juxtaposition, before positive conclusions may be reached as to the sequence of crystallization.

E. A. Stephenson

Chicago

Relations of Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico. By Willis T. Lee. Prof. Paper, U.S. Geol. Surv. No. 95-C, 1915. Pp. 27–58, pl. 1, figs. 11.

In this paper physiographic principles are applied to certain phases of the stratigraphy of the southern Rocky Mountains. The geographic conditions during the Mesozoic are discussed and a large number of Cretaceous sections are considered. This study indicates that this basin of Cretaceous deposition was deepest in northern Colorado and southern Wyoming, and that the main mass of sediment came from an ancient land farther west. The sections show, moreover, that the sandstone formations near this ancient continent become thinner eastward, toward the present Rocky Mountains, and are replaced by shales. The author concludes that the conformable Cretaceous formations up to and including the Laramie once extended across the present site of the mountains. Downward warping and deposition in this basin was followed by uplift and erosion. This change is believed to mark the close of the Cretaceous. The formations deposited after the uplift (the post-Laramie formations) belong in the Tertiary.

H. R. B.

Review of the Pleistocene of Europe, Asia, and Northern Africa. By Henry Fairfield Osborn. Annals N.Y. Acad. Sci., XXVI, 1915, pp. 215–315; figs. 20, tables 4.

This paper is a revision for the German edition of chap. vi of the author's *The Age of Mammals.*

H. R. B.

Geological Relations and Some Fossils of South Georgia. By J. W. Gregory. Trans. Roy. Soc. Edin., L, 1915, pp. 817–22, pls. 2.

The outcropping rocks are described as consisting of a metamorphic series of probable Ordovician or Silurian age and a series of marine Mesozoic rocks associated with volcanic tuffs. There is no evidence of Cenozoic volcanic activity, and the igneous rocks are not of distinctly Andean types. Suess believed that the Andes extended in a great horseshoe curve through South Georgia to the South Orkneys and Graham Land.

H. R. B.

The Jaw of the Piltdown Man. By Gerret S. Miller, Jr. Smith. Misc. Coll., LXV, No. 12, 1915. Pp. 31, pls. 5.

In 1912 the right half of an apelike jaw, a portion of a human brain case, and other human bone fragments were found in a gravel pit at Piltdown, Sussex, England, associated with an interglacial (early Third?) fauna. Assuming that these remains represented parts of one individual, Woodward established the genus *Eoanthropus*, characterized by the combination in one skull of a human brain case and an apelike jaw.

Miller now compares casts of these fragments with specimens of Pongidae and Hominidae in the National Museum and finds that the brain case shows fundamental characters not known except in the genus Homo, while the other fragments show equally diagnostic features hitherto unknown except among members of the genus *Pan* (chimpanzees). For the Pleistocene species represented by Woodward's *Eoanthropus*, Miller proposes the name *Pan vetus*.

H. R. B.

The Shinumo Quadrangle, Grand Canyon District, Arizona. By L. F. Noble. U.S. Geol. Surv., Bull. No. 549, 1914. Pp. 100, pls. 18, fig. 1.

This bulletin presents the results of a detailed study of the western part of the Kaibab division of the Grand Canyon. The section includes rocks of Archean, Algonkian, Cambrian, Mississippian, and Pennsylvanian age. The lower or Unkar group of the Grand Canyon Series (Algonkian), in particular, is treated in considerable detail. The map which accompanies the bulletin represents the first detailed mapping done in the Grand Canyon region.

H. R. B.

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EDITED BY

THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY

With the Active Collaboration of

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ON THE AMOUNT OF INTERNAL FRICTION DEVELOPED IN ROCKS DURING DEFORMATION AND ON THE RELATIVE PLASTICITY OF DIFFERENT TYPES OF ROCKS

FRANK D. ADAMS, D.Sc., F.R.S., AND J. AUSTEN BANCROFT, M.A., Ph.D.
McGill University, Montreal

INTRODUCTION

At the meeting of the Geological Society of America held in Albany in the year 1900, a brief résumé of the experimental work on the flow of marble carried out by Adams and Nicolson was presented to the Society, and in the discussion which followed the reading of this paper a number of interesting points were suggested by various speakers as worthy of experimental investigation. Among these was one put forward by Dr. G. K. Gilbert, which, in a letter to the authors, he subsequently formulated as follows:

> It has been thought that great pressure breaks down the structure called solidity and so reduces viscosity that very little differential stress is necessary to produce flow. It is thought that the strength of rocks is practically unaffected by pressure, in which case flow should begin only when differential stress equals the crushing strength of the material as conditioned by the temperature. It is certainly conceivable also that the strength of rocks is increased by pressure, so that the production of flow requires differential stress greater than the crushing stress as conditioned by the temperature. I hope your experimentation may be brought to throw light upon this point.

The sense in which certain terms are used in this quotation is not quite clear, but we understand the question put forward by Dr. Gilbert to be as follows:

A unit cube of any rock—granite for instance—is submitted to pressure in a testing machine on the earth's surface. It will give away or break down under a certain load—this is termed its crushing load.

If this cube of rock were imbedded deep within the earth's crust, great pressure would be exerted upon it from all sides. Such being the case, and omitting from consideration the influence of temperature, would the rock (1) be reduced to a condition which approaches fluidity and move at once if the pressure in one direction became slightly greater than that in another? Or (2) would the rock become deformed only when this additional pressure in one direction was equal to its crushing load at the surface? Or (3) would the rock show an increased resistance to deformation and require a much greater additional pressure in one direction to deform it than was required to crush it at the surface?

A few preliminary trials which served to open up the experimental investigation of this problem were undertaken some years ago by Dr. Adams in association with Dr. Ernest G. Coker, then Associate Professor of Civil Engineering at McGill University. Dr. Coker subsequently resigned his position at McGill University to accept the professorship of mechanical engineering and applied mathematics at the Finsbury Technical College in London, and for a time the work was discontinued. Dr. Bancroft, however, some years later coming to McGill University, the investigation was resumed. It has extended over a period of several years. The writers desire to acknowledge their indebtedness to the Carnegie Institute of Washington, the work having been carried out under a grant received from that body.

ROCKS EXAMINED

The following rocks were examined:

White alabaster, Castelino, Italy.

White marble, Carrara, Italy.

Black Belgian marble ("Noir fin").

White dolomite, Cockeysville, Maryland, U.S.A.

Steatite ("Albarine"), Virginia, U.S.A.

Slate, New Rockland, Province of Quebec, Canada.

Sandstone, Cleveland, Ohio, U.S.A.

Granite, Baveno, Italy.

Olivine diabase, Sudbury, Province of Ontario, Canada.

For the purposes of comparison experiments were also conducted with metallic copper and metallic lead.

Detailed petrographical descriptions of these rocks, with the exception of the alabaster, dolomite, steatite, and slate, have been given in a former paper.[1] It is necessary here, therefore, to refer briefly to the character of these four rocks only.

Alabaster, Castelino, Italy.—Under the microscope the rock is seen to be composed of an aggregate of small grains of gypsum which are clear, colorless, and approximately equal in size. The individual grains display a tendency to elongation in one direction, thus giving the rock a very faint foliation. The columns of alabaster used in the experiments were cut from a single uniform block of this rock in such a manner that their longer axes were parallel to this indistinct foliation.

Dolomite, Cockeysville, Maryland, U.S.A.—This is a rather fine-grained, white, granular dolomite, very pure in character and uniform in composition, containing $CaCO_3$ and $MgCO_3$ in almost exactly their molecular proportions. It presents the appearance of a white marble and is extensively quarried as such. Thin sections of the rock, when examined under the microscope, show that it is composed of a mosaic of grains of the mineral dolomite, more or less irregular in shape and varying somewhat in size. Between crossed nicols, they present a uniform extinction or show only the faintest strain shadows. They are very seldom twinned.

Steatite, Virginia, U.S.A.—This steatite is placed on the market under the name of "albarine." The columns employed in the experiments were cut from a perfectly uniform slab of this rock

[1] "An Investigation into the Elastic Constants of Rocks More Especially with Reference to Their Cubic Compressibility," by F. D. Adams and E. G. Coker, The Carnegie Institute of Washington, 1906; see also *American Journal of Science*, XXII (August, 1906).

with dimensions of $10'' \times 11'' \times 1\frac{1}{4}''$. Under the microscope the rock is seen to possess a distinct foliation parallel to the broad surface of the slab. All of the columns were cut from this slab with their longer axes parallel to the foliation. In thin sections under the microscope the rock is seen to be composed chiefly of chlorite, talc and dolomite, numerous small crystals and grains of magnetite, and a few grains of pyrite are also present. The two minerals, chlorite and talc, make up by far the greater portion of the rock, the chlorite being somewhat more abundant than the talc. Both occur as plates and sheaflike aggregates, and both possess a very distinct cleavage parallel to which extinction takes place. The dolomite is present both in large rhombohedral individuals and as small irregular granules which possess a linear arrangement parallel to the foliation of the rock. None of the grains of dolomite show either twinning or strain shadows. Having been cut parallel to the foliation, it is not surprising that the columns of this rock employed in the experiments bulged assymetrically when deformed, and hence a larger number of experiments were made with the steatite than with the other rocks, in order that accurate average results might be secured.

Slate, New Rockland, Quebec, Canada.—This is a typical fine-grained slate, black in color, uniform in character, and possessing an excellent cleavage. By means of a diamond drill cores were taken perpendicular to the cleavage of the slate, and from these the columns of slate used in the experiments were prepared.

Under the microscope this slate is found to be composed essentially of minute flakes of two minerals, one of which is apparently kaolin and the other muscovite. In general, the kaolin is much more abundant than the muscovite, from which it can be distinguished in that it possesses a lower double refraction and is not quite so transparent. Within a few extremely narrow bands of the slate the muscovite preponderates. A few minute grains of quartz are interposed between the flakes of muscovite and kaolin. A considerable number of very small flakes of black, opaque, carbonaceous matter, abundant, minute, needle-like crystals of rutile, and a very few widely scattered grains of pyrrhotite are also present. The

rutile crystals are brownish in color and occasionally display the geniculated twinning that is characteristic of this species.

The foliation of the slate explains the lack of symmetry in the expansion of columns of this rock during deformation.

The *Copper* used in these experiments was taken from a rod 1 inch in diameter, representing a good commercial grade of this metal. Prior to being turned into columns for the experiments, the pieces cut from the rod were annealed by being heated to bright redness in the coal fire of a forge, being then allowed to cool down gradually.

The *Lead* employed in the experiments was "assay lead" which, in order to free it from all air bubbles, was melted down and cast in a heated iron mold, which was then allowed to cool slowly.

METHODS EMPLOYED

Several long round bars of nickel steel $2\frac{1}{2}$ inches in diameter, all of identical composition and from the same heat, and all having been submitted to identical treatment in their manufacture, were secured. For these the authors are indebted to the Bethlehem Steel Company, which placed them at their disposal for the purpose of the present investigation.

This steel, which is very uniform in character, possesses a high tensile strength, as well as a high elastic limit, and has the following chemical composition:

Carbon	.30 per cent
Manganese	.74 per cent
Silicon	.162 per cent
Phosphorus	.035 per cent
Sulphur	.038 per cent
Nickel	4.740 per cent

The bars were sawed into lengths of about $3\frac{1}{4}$ inches. These were then bored and turned into tubes, the longitudinal sections of which, with the final dimensions, are shown in the upper half of Fig. 1. Two sets of these tubes were prepared, differing only in the thickness of the wall of the central portion of the tube. In the first set this has a thickness of 0.33 centimeter, while in the second

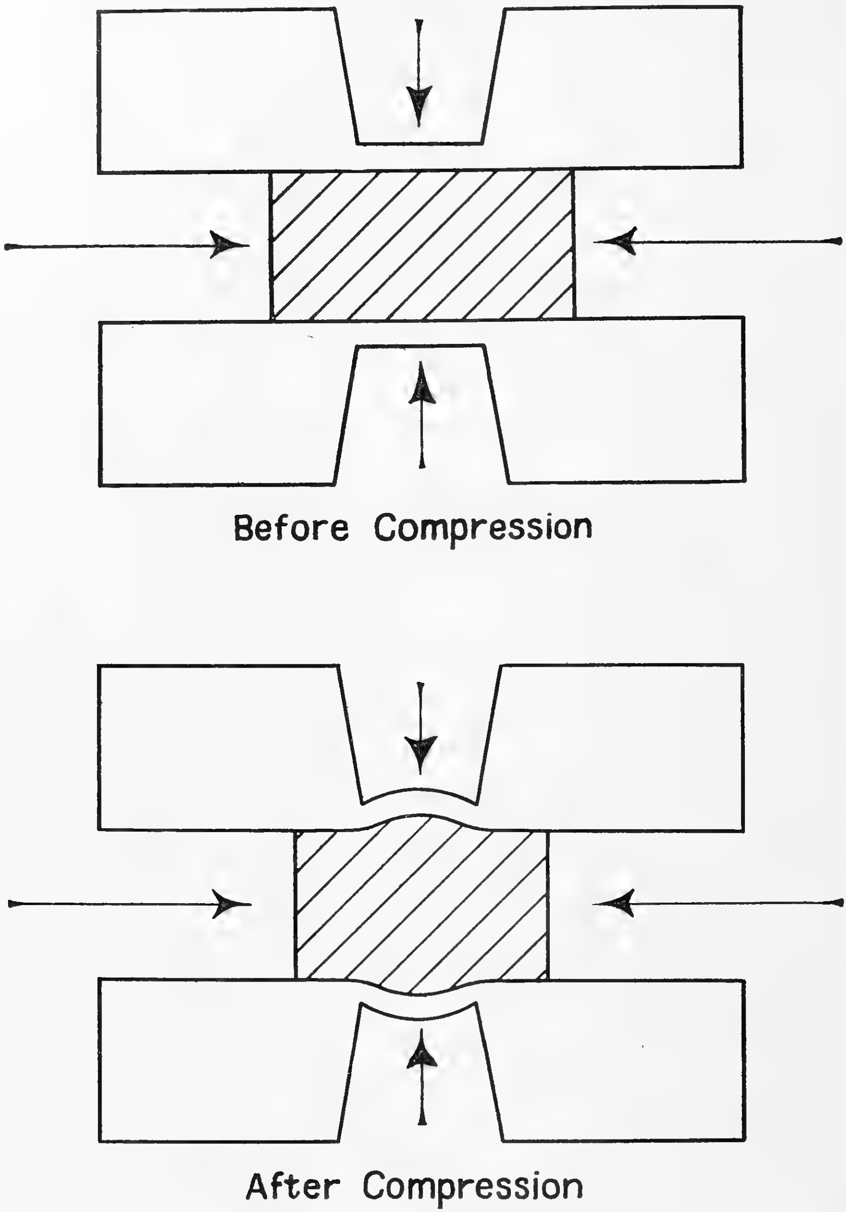


FIG. 1.—Longitudinal section through steel cylinder with wall 0.33 cm. thick, and inclosing one of the rock columns (natural scale).

set the thickness is 0.25 centimeter. The interior diameter of the tube in both sets is of such a size that it will just receive a column of rock 2 centimeters in diameter. The inner surface of the tube in every case was not only perfectly smooth, but highly polished. The angle of the bevel, by which the thickness of the wall is reduced at the middle of the tube, was adopted after a long series of preliminary experiments, which proved it to be that which was demanded by the conditions to be secured. Pistons fitting accurately into either end of these tubes were then made of chromium tungsten steel, suitably tempered by being heated, quenched in oil, and then ground to the exact dimensions required.

Large blocks of each of the rocks having been secured, rough columns of them were bored out by means of a hollow-bit diamond drill, care being taken in the case of each rock to have all the columns bored out of the rock in the same direction, that is, parallel to one another, so that any possible variations due to rift, grain, or incipient foliation were avoided. These rough columns were then reduced to the exact size required, by being ground down in a lathe by means of revolving carborundum wheels of different degrees of fineness, and were finally highly polished. When completed the columns were of such a size that they would just pass into the steel tubes at the ordinary temperature, the tube inclosing the column with an absolutely perfect mechanical fit. The column was in each case 4 centimeters long and 2 centimeters in diameter. While the column was thus fitted accurately into the tube, it could, by the exertion of a certain amount of pressure, be moved up and down within the tube. The column of rock, when inserted into the tube, was so placed that its center was exactly in the center of the thinner portion of the tube, as shown in the diagram, the extremities of the column being in this way supported by the walls of the thicker portion of the tube at either end.

The pressure to which the rock was submitted was obtained by a Wicksteed testing machine set up in the Testing Laboratory of the Macdonald Engineering Building of McGill University. This machine has a capacity of 100 tons and, when loaded to its capacity, is sensitive to a load of 4 pounds. Unfortunately, being graduated to read only in tons and pounds, it was necessary to obtain the data

of the research in these units. In presenting the final results, however, the data for the conversion of these into a unit more generally employed in physical investigations are given.

The extensometer employed for the purpose of measuring the expansion of the tube under pressure was a simplified form of the type designed by Professor Coker and described in the *Proceedings of the Royal Society of Edinburgh*, XXV (1904–5). It was affixed to the opposite points of the steel tube on the plane of maximum deformation and showed the expansion, multiplied by two, by means of a fine line moving over a graduated scale, which was read by a telescope placed at a distance of several feet.

In a number of experiments two extensometers were employed, which were applied to the tube in the plane of maximum deformation, but in directions at right angles to one another. In this way it was ascertained that the bulge which the steel tube displayed under pressure was nearly symmetrical, but in order that any error which might arise from a single measurement might be eliminated, in almost all cases the two extensometers employed were affixed to the tube at right angles to one another, and the mean of the two readings was secured. By means of this form of extensometer and by reading with a telescope, it was possible to measure an increase on the diameter of the tube amounting to only 0.0005 inch. The steel tube inclosing the rock column, with the extensometers in position, the whole set up in the press ready for the application of pressure, is shown in Fig. 2.

The method adopted for measuring the internal friction developed in the rock by deformation was as follows:

A column of rock, Carrara marble, first was taken, having the dimensions already referred to. This was inclosed in a tube of nickel steel, as above described; the tube had a wall thickness of 0.25 centimeter at its thinner portion. As will be seen from Fig. 1, the middle portion of the marble column is inclosed by the thinner portion of the tube, while the ends of the column are held by the thicker portion of the tube wall. In this way the rock is prevented from flowing up between the tube and the pistons and thus from escaping from the tube. With a tube of this shape and these dimensions, the movement of the rock under pressure is confined

to the middle portion of the column, which is surrounded by the thinner portion of the tube. The pistons being inserted and the whole properly set up in the testing machine, the pressure was

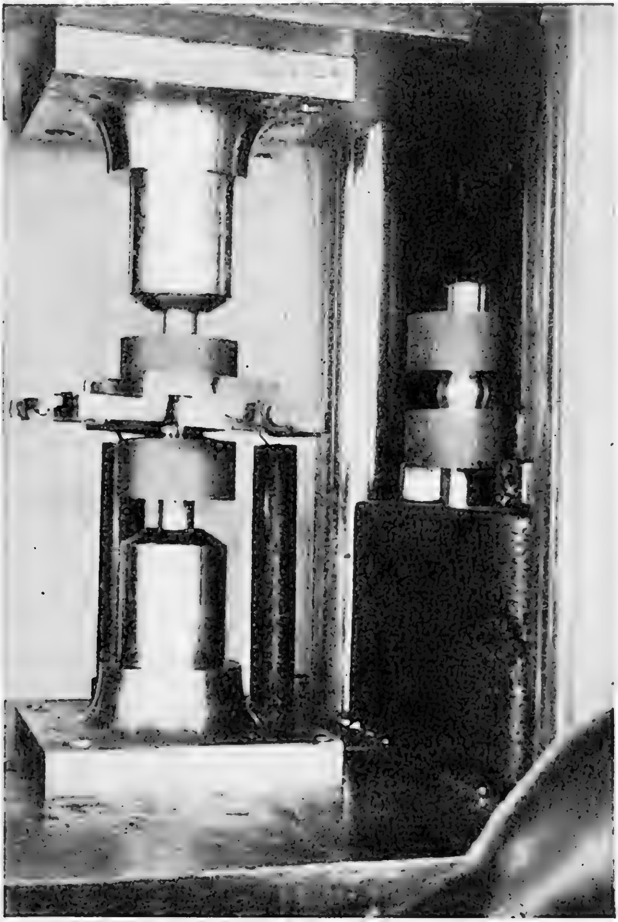


Fig. 2.—Steel cylinder, inclosing a rock column and with the two extensometers in position, set up in the Wicksteed press. To the right a bulged cylinder is shown as it appears at the close of an experiment.

applied in successive increments of 1,000 pounds. The extensometer showed no yielding of the inclosed rock until a load of about 12,000 pounds had been reached, when a very slight distension of

the tube was indicated. Up to this point, the marble, being an elastic body, was undergoing cubic compression, the pressure exerted by the machine and the resistance exerted by the steel collar being equal. The slight distension of the steel tube at a load of 12,000 pounds is due to the elastic deformation of the marble. After each additional increase of 1,000 pounds to the load, extensometer readings were taken every 30 seconds until four successive readings were identical, that is to say, until no movement that could be registered on the scale took place during a period of 2 minutes. The pressure was then increased by another 1,000 pounds and a similar series of readings were taken. This was continued until the bulging steel tube showed signs of rupture or was actually ruptured by the movement of the inclosed rock. The time which elapsed between the first application of pressure and the final rupture of the tube, that is to say, the duration of the experiment, differed somewhat in the different experiments, but may be said to be about four hours.

During the time which elapses from the point when the elastic limit of the rock is exceeded to that at which the tube fails, the inclosed rock is undergoing deformation with extreme slowness and by internal movements of one kind or another, which give rise to what may be termed a plastic flow.

At the commencement of the experiment the column of marble had the form and dimensions represented in the upper half of Fig. 1. When at the conclusion of the experiment the test piece was placed in a lathe and the steel collar was turned off, the specimen of marble was set free. It was still intact, unbroken, and, when tested in compression, was found to be very nearly as strong as a piece of the original marble of the same shape and size. It now had the form represented in the lower half of Fig. 1.

A photograph of a column of rock, before and after deformation, the rock, however, in this particular case being steatite, is shown in Fig. 3.

The pressure which was applied to the marble column effected two results. It overcame the pressure (or resistance) exerted upon the sides of the column by the inclosing tube of steel, and it overcame the internal friction developed within the rock during its

change of shape. If it were possible, therefore, to ascertain the amount of the pressure (or lateral resistance) exerted by the inclosing tube, it would be possible by subtracting this from the total load employed to determine the load which was required to overcome the internal friction of the rock under the conditions of the experiment.

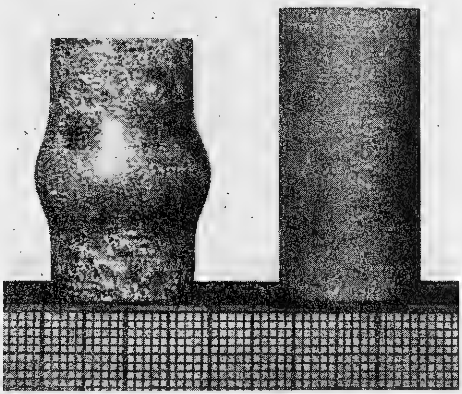


FIG. 3.—Photograph of columns of steatite before and after deformation. The smaller divisions of the scale below are millimeters.

In order to determine the amount of pressure required to effect the progressive deformation of the tube, i.e., the amount of pressure exerted by the tube on the inclosed rock during the successive stages of deformation, a series of steel tubes, identical in every respect with those employed in the experiment just described, were taken and were deformed in a precisely similar manner, except that these tubes were filled with soft tallow, instead of being occupied by a column of marble. This material was selected as being one which moves with the development of an amount of internal friction which is so small that it was negligible in the present case. In carrying out the experiment with tallow, we found it necessary to slightly alter the shape of the steel pistons, the ends inserted in the steel tube being turned so as to present a somewhat concave face, as shown in Fig. 4, the outer margins having a thin feather edge. When pressure is brought to bear upon these pistons, this thin edge expands slightly, thus pressing against the walls of the tube and preventing the tallow from escaping between the piston and the wall. It was found that in this way the deformation of the tube could be readily effected.

The objection might be put forward that, while undoubtedly the tallow possesses at ordinary atmospheric pressure an internal friction which is quite negligible, this material under the pressure to which it must be subjected in order to deform the steel tube might develop an amount of internal friction and a rigidity which would be by no means negligible.

In order to ascertain whether such was the case, companion experiments were made, using the same pistons, but employing

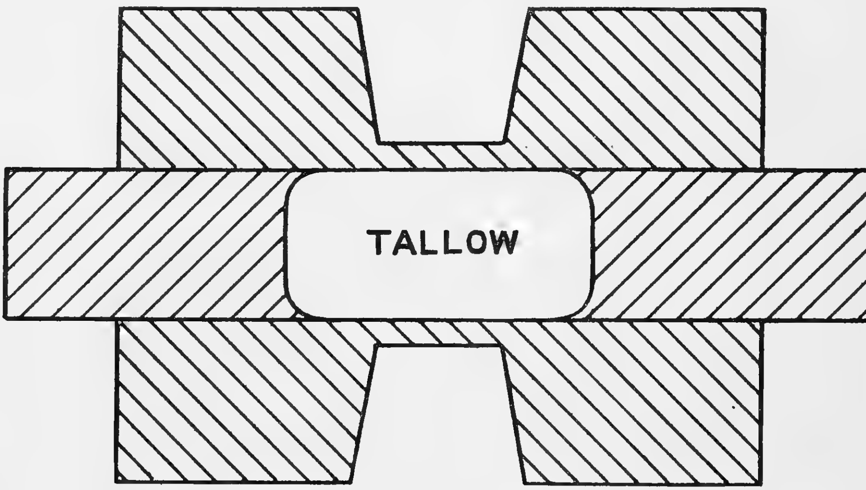


FIG. 4.—Longitudinal section through steel cylinder, showing the type of piston used when deforming the steel with tallow.

water in one case and oil in another, instead of tallow. It was found that the deformation of the tube could be effected by either of these materials, although, when water was employed, it was necessary to raise the pressure rapidly at first to cause the feather edges of the pistons to expand and make the joint tight, thus preventing the water from escaping. This series of comparative experiments was carried out with loads up to 19,000 pounds, at which pressure the tubes failed, and it was found that under these pressures the three substances mentioned—water, oil and soft tallow—showed no difference in viscosity which could be detected. The tallow, of course, undoubtedly possesses a somewhat greater inter-

nal friction than the water, but at the range of pressure to which it was submitted in the present investigation this difference is not noticeable and may therefore be neglected. The tallow, however, being more convenient for purposes of experiment, was employed in a further series of comparative experiments.

There was one other possible source of error, namely, the friction between the walls of the tube and the thin feather edge of the hollow-faced piston used in the experiments with the tallow. In the experiments with a column of rock a flat-faced piston was of course employed, and this source of friction was thus eliminated. In order to ascertain the amount of this friction in the case of the tallow, another steel tube was constructed, identical in all respects with those used in this investigation. One end of it, however, was closed so that it would be necessary to employ only a single piston, and through the closed end a small copper tube was inserted, which led to a powerful pump provided with an accurate pressure gage. The whole apparatus having been filled with water supplied by the pump, the steel tube with its cup-shaped piston was placed in a 75-ton Emery testing machine, and the piston slowly forced into the fluid, the pressure required to do this being noted at every stage on the testing machine and also on the gage fitted to the pump. In this way the pressure necessary to force the piston forward was measured at each additional increment of load applied to the piston by the Emery machine. As a result of a series of trials, it was ascertained that the friction on the feather edges of the piston amounted on an average to only 290 pounds, so that, in view of the very heavy pressure employed in this investigation, the error thus introduced is so small that it may be neglected.

It having been ascertained that soft tallow was a material which for the purposes of this investigation might be considered to move without the development of internal friction, a series of experiments were made with steel tubes identical in character and dimensions with those employed to inclose the marble, but soft tallow was substituted for marble. The two series of experiments were carried out in exactly the same manner in every detail, except that in the tubes filled with tallow the load was raised by increments of 500 pounds, instead of 1000 pounds, and the readings were taken

every 15 seconds instead of every 30 seconds till they remained constant for at least 5 consequent readings. This change was necessitated in order to standardize the conditions in the two series of experiments, since, when the tube was filled with tallow, the whole load was applied to overcome the resistance of the tube, while, when the place of the tallow was taken by marble, a portion of the load was applied to overcome the internal friction of the rock, and the movement was slower. By modifying the procedure, as above mentioned, in the case of the tubes filled with tallow an identical deformation was secured in both cases.

When columns of rock are inclosed in the steel tubes and deformation is carried out in the manner described, the impending rupture of the steel tube, which marks the conclusion of the experiment, is indicated by the appearance of a series of sharply marked vertical lines on the bulged wall of steel which inclosed the deformed rock. If the experiment is continued, the tube splits along one of these vertical lines, and the inclosed rock becomes visible, and, if the pressure is still maintained, the resistance along the line of rupture being removed, the rock along this line crumbles and is forced out of the fissure in the form of a powder.

In the case of the experiments in which tallow was employed in place of a column of rock, the completion of the test is marked by the development of a vertical fissure in the thin portion of the steel tube in the usual manner. So soon as this appears, however, and usually before the load can be taken off the testing machine, a fragment of the thin steel wall, bounded on one side by the fissure in question and at the top and bottom by the thicker portion of the steel tube, opens out like a door on its hinges and is instantly torn off and with a loud report is shot across the room with great violence. It therefore was necessary in the case of these experiments that the observer should always be protected from these projectiles, the importance of this protection being emphasized in the case of one of the experiments by the fact that the piece of steel struck and split in two the piece of hard wood, a quarter of an inch thick, which protected the observer's head.

In order to make quite sure that the form and outline of the bulge assumed by the tube in the case of the experiments with the

different rocks was the same, a special series of experiments to decide this question was made, employing copper, lead, marble, Belgian black, and granite. In each instance the experiment was carried to the point where the bulge or expansion of the diameter amounted to 0.030. The cylinder was then removed, and by using an electric arc light in a dark room a sharp shadow of the outline of the bulged cylinder was cast upon sensitive paper, removed at such a distance that the photograph enlarged the outline of the cylinder approximately 18 times. The cylinder was then placed in the Wicksteed machine, and the bulge increased to 0.110, and a similar photograph taken. By a comparison of the photographs it was found that the outline of the deformed wall was essentially identical in all cases.

As has been mentioned, from two to five experiments were made in the case of each rock when inclosed in a 0.25-centimeter tube and the same number with each rock inclosed in a tube having a wall thickness of 0.33 centimeter. The mean of the closely concordant results was then worked out in each case, and the figures obtained are presented in Tables I and II. These represent the data yielded by the experimental work.

The necessary data having been thus secured, a curve was plotted presenting these graphically in the case of each experiment. In these curves the exact amount of the load required to produce any required bulge or distension of the tube is shown from the point when the first movement can be detected until the final rupture of the tube takes place. The curves for the several experiments with Carrara marble inclosed in the steel tubes with a 0.25-centimeter wall are shown in Fig. 5 (p. 620). A curve representing the mean of the results obtained in the several experiments is also given. In Fig. 6 (p. 621) this curve of the mean of the results obtained from the marble inclosed in a 0.25-centimeter tube is reproduced, and below it is the mean of the curves obtained from tallow when inclosed in a 0.25-centimeter steel tube.

Since the tallow, as has been shown, offers itself no measurable resistance to deformation under the conditions of the experiment, the curve in the tallow experiments shows merely the resistance offered to deformation by the steel tube itself.

TABLE I

AMOUNT OF DEFORMATION, IN INCHES, OF THE SEVERAL ROCKS WHEN INCLOSED IN THE STEEL CYLINDERS HAVING A WALL THICKNESS OF 0.25 CENTIMETER

LOAD IN POUNDS*	TALLOW	LEAD	COPPER	ROCKS EMPLOYED								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
2,000	0.0002	....	....	....	....	....	....	....	....	....	....	....
3,000	.0005	....	....	....	....	....	....	....	....	....	....	....
4,000	.0008	....	....	....	0.0003	....	....	....	....	....	....	....
5,000	.0013	0.0004	....	....	.0003	....	....	....	....	....	....	....
6,000	.0018	.0010	....	....	.0003	....	....	....	....	....	....	....
7,000	.0025	.0015	....	0.0003	.0003	....	....	....	....	....	....	....
8,000	.0032	.0020	0.0003	.0004	.0003	....	....	....	....	....	....	....
9,000	.0062	.0038	.0005	.0005	.0003	....	....	....	....	....	....	....
10,000	.0130	.0075	.0010	.0006	.0003	....	0.0003	....	....	....	....	....
11,000	.0216	.0139	.0018	.0006	.0008	....	.0005	....	....	....	....	....
12,000	.0323	.0220	.0023	.0008	.0009	....	.0006	....	....	....	....	....
13,000	.0483	.0330	.0038	.0009	.0009	....	.0006	....	....	....	....	....
14,000	.0748	.0550	.0050	.0009	.0010	....	.0008	....	....	....	....	....
15,000	0.1097	.0843	.0073	.0013	.0013	....	.0009	....	....	....	....	....
16,000	....	0.1133	.0098	.0013	.0013	0.0003	.0009	....	....	....	....	....
17,000	....	....	.0120	.0016	.0014	.0005	.0016	....	....	....	....	....
18,000	....	....	.0148	.0021	.0016	.0005	.0018	....	....	....	....	....
19,000	....	....	.0175	.0026	.0021	.0005	.0018	....	....	....	....	....
20,000	....	....	.0203	.0043	.0028	.0008	.0021	....	....	....	....	....
21,000	....	....	.0233	.0068	.0031	.0008	.0021	....	....	....	....	....
22,000	....	....	.0260	.0103	.0036	.0010	.0023	....	....	....	....	....

23,000			.0295	.0145	.0045	.0010	.0028					
24,000			.0328	.0199	.0063	.0015	.0030					
25,000			.0365	.0258	.0080	.0023	.0035					
26,000			.0403	.0323	.0098	.0030	.0043				0.0003	
27,000			.0445	.0386	.0126	.0040	.0051				.0003	
28,000			.0488	.0462	.0151	.0065	.0068				.0004	
29,000			.0535	.0532	.0184	.0083	.0078	0.0005			.0004	
30,000			.0583	.0608	.0218	.0125	.0085	.0009	0.0005		.0004	
31,000			.0640	.0694	.0258	.0155	.0110	.0011	.0010		.0006	
32,000			.0708	.0779	.0318	.0198	.0126	.0011	.0010		.0006	0.0004
33,000			.0768	.0872	.0353	.0238	.0139	.0011	.0010		.0009	.0004
34,000			.0840	.0972	.0419	.0283	.0169	.0013	.0010		.0009	.0004
35,000			.0923	.1072	.0473	.0330	.0181	.0016	.0010		.0009	.0004
36,000			.0995	.1184	.0556	.0368	.0208	.0031	.0013		.0009	.0004
37,000			0.1093	.1300	.0868†	.0423	.0234	.0036	.0013		.0014	.0004
38,000				0.1512	.0893	.0483	.0268	.0040	.0018		.0014	.0004
39,000					.0935	.0535	.0296	.0040	.0020		.0014	.0004
40,000					.0990	.0593	.0326	.0045	.0020	0.0004	.0014	.0004
41,000					.1048†	.0650	.0354	.0048	.0020	.0008	.0014	.0004
42,000					.1123	.0738	.0386	.0053	.0023	.0008	.0018	.0004
43,000					.1231	.0800	.0416	.0060	.0023	.0009	.0018	.0008
44,000					.1324	.0880	.0464	.0075	.0025	.0009	.0018	.0008
45,000					.1458	.0958	.0511	.0091	.0030	.0009	.0020	.0010
46,000					0.1559	.1050	.0560	.0108	.0033	.0010	.0020	.0010
47,000						.1145	.0613	.0129	.0038	.0011	.0025	.0010
48,000						.1235	.0658	.0153	.0040	.0011	.0025	.0010
49,000						.1323	.0716	.0181	.0053	.0013	.0028	.0010
50,000						.1398	.0768	.0224	.0063	.0013	.0031	.0010
51,000						.1493	.0819	.0255	.0085	.0015	.0031	.0011
52,000						0.1580	.0879	.0301	.0108	.0018	.0035	.0013
53,000							.0936	.0351	.0135	.0020	.0040	.0014
54,000							.0989	.0406	.0165	.0021	.0043	.0015
55,000							0.1063	0.0471	0.0210	0.0022	0.0043	0.0016

* Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

† Between the daggers in the column pertaining to Alabaster the results are irregular because in one of the experiments there was an impact delivered to the specimen, as explained in the discussion of Fig. 12.

TABLE I—*Continued*

Load in Pounds*	Tallow	Lead	Copper	Rocks Employed								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble, ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
56,000	...	...	...	...	...	...	0.1109	0.0546	0.0258	0.0026	0.0048	0.0016
57,000	...	...	...	...	...	...	.1155	.0604	.0313	.0085	.0051	.0018
58,000	...	...	...	...	...	...	.1219	.0671	.0360	.0091	.0056	.0021
59,000	...	...	...	...	...	...	.1282	.0754	.0413	.0103	.0070	.0023
60,000	...	...	...	...	...	...	.1349	.0818	.0485	.0108	.0078	.0023
61,000	...	...	...	...	...	...	.1405	.0895	.0543	.0119	.0084	.0024
62,000	...	...	...	...	...	...	.1459	.0968	.0613	.0150	.0089	.0026
63,000	...	...	...	...	...	...	0.1505	.1041	.0665	.0335	.0098	.0026
64,000	...	...	...	...	...	...	...	.1110	.0723	.0447	.0113	.0029
65,000	...	...	...	...	...	...	...	.1178	.0838	.0540	.0125	.0031
66,000	...	...	...	...	...	...	...	.1265	.0898	.0680	.0136	.0033
67,000	...	...	...	...	...	...	...	.1344	.0980	.0801	.0159	.0036
68,000	...	...	...	...	...	...	...	.1410	.1073	.0905	.0178	.0036
69,000	...	...	...	...	...	...	...	.1494	.1143	.0981	.0206	.0041
70,000	...	...	...	...	...	...	...	.1569	.1235	.1116	.0247	.0045
71,000	...	...	...	...	...	...	...	0.1651	.1315	.1223	.0289	.0049
72,000	...	...	...	...	...	...	...	...	.1395	.1316	.0330	.0050
73,000	...	...	...	...	...	...	...	...	.1540	.1432	.0396	.0055
74,000	...	...	...	...	...	...	...	...	0.1648	0.1521	.0475	.0060
75,000	...	...	...	...	...	...	...	...	...	...	.0554	.0069
76,000	...	...	...	...	...	...	...	...	...	...	.0650	.0076
77,000	...	...	...	...	...	...	...	...	...	...	.0744	.0089
78,000	...	...	...	...	...	...	...	...	...	...	.0839	.0121
79,000	...	...	...	...	...	...	...	...	...	...	.0939	.0290

80,000	....	....	....	....	....	....	....	....	....	....	.1038	.0434
81,000	....	....	....	....	....	....	....	....	....	....	.1131	.0554
82,000	....	....	....	....	....	....	....	....	....	....	.1230	.0636
83,000	....	....	....	....	....	....	....	....	....	....	.1321	.0708
84,000	....	....	....	....	....	....	....	....	....	....	.1405	.0793
85,000	....	....	....	....	....	....	....	....	....	....	0.1505	.0868
86,000	....	....	....	....	....	....	....	....	....	....	....	.0961
87,000	....	....	....	....	....	....	....	....	....	....	....	.1000
88,000	....	....	....	....	....	....	....	....	....	....	....	.1143
89,000	....	....	....	....	....	....	....	....	....	....	....	.1234
90,000	....	....	....	....	....	....	....	....	....	....	....	.1308
91,000	....	....	....	....	....	....	....	....	....	....	....	.1418
92,000	....	....	....	....	....	....	....	....	....	....	....	0.1498
Number of experiments performed	3	2	2	4	2	2	4	2	2	2	2	2
Average duration of each experiment	0 hr. 52 min.	1 hr. 10 min.	1 hr. 32 min.	2 hr. 11 min.	2 hr. 22 min.	4 hr. 0 min.	4 hr. 0 min.	4 hr. 32 min.	4 hr. 14 min.	3 hr. 49 min.	4 hr. 56 min.	4 hr. 11 min.

*Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

TABLE II

AMOUNT OF DEFORMATION, IN INCHES, OF THE SEVERAL ROCKS WHEN INCLOSED IN THE STEEL CYLINDERS HAVING A WALL THICKNESS OF 0.33 CENTIMETER

Load in Pounds*	Tallow	Lead	Copper	Rocks Employed								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble, ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
4,000	......	......	......	......	......	......	......	......	......	......	......	......
5,000	0.0004	......	......	......	......	......	......	......	......	......	......	......
6,000	.0005	0.0005	......	......	......	......	......	......	......	......	......	......
7,000	.0008	.0008	......	......	......	......	......	......	......	......	......	......
8,000	.0010	.0013	......	......	......	......	......	......	......	......	......	......
9,000	.0012	.0013	......	......	......	......	......	......	......	......	......	......
10,000	.0018	.0019	0.0003	......	......	......	......	......	......	......	......	......
11,000	.0028	.0025	.0006	0.0004	......	......	......	......	......	......	......	......
12,000	.0055	.0040	.0010	.0005	......	......	......	......	......	......	......	......
13,000	.0095	.0080	.0013	.0007	0.0004	......	......	......	......	......	......	......
14,000	.0153	.0116	.0017	.0009	.0006	......	0.0005	......	......	......	......	......
15,000	.0212	.0173	.0018	.0010	.0006	......	.0008	......	......	......	......	......
16,000	.0280	.0240	.0023	.0013	.0006	0.0003	.0010	......	......	......	......	......
17,000	.0367	.0313	.0026	.0013	.0008	.0003	.0010	......	......	......	......	......
18,000	.0475	.0419	.0033	.0017	.0008	.0005	.0010	......	......	......	......	......
19,000	.0645	.0560	.0040	.0021	.0009	.0005	.0010	......	......	......	......	......
20,000	.0848	0.0805	.0050	.0025	.0009	.0008	.0013	......	......	......	......	......
21,000	0.1152	......	.0065	.0028	.0013	.0008	.0013	......	......	......	......	......
22,000	......	......	.0078	.0029	.0014	.0008	.0015	0.0003	......	......	......	......
23,000	......	......	.0098	.0034	.0015	.0008	.0018	.0003	......	......	......	......
24,000	......	......	.0117	.0038	.0019	.0008	.0020	.0003	......	......	......	......

25,000			.0138	.0050	.0026	.0008	.0020	.0003				
26,000			.0155	.0071	.0029	.0010	.0020	.0003				
27,000			.0187	.0093	.0031	.0010	.0023	.0003				
28,000			.0212	.0116	.0038	.0010	.0023	.0004	0.0003			
29,000			.0238	.0146	.0043	.0010	.0028	.0006	.0003			
30,000			.0273	.0173	.0051	.0011	.0030	.0008	.0003			
31,000			.0305	.0212	.0061	.0013	.0040	.0009	.0003			
32,000			.0345	.0237	.0075	.0013	.0040	.0010	.0007			
33,000			.0387	.0265	.0089	.0018	.0050	.0011	.0007			
34,000			.0426	.0306	.0114	.0043	.0063	.0011	.0007			
35,000			.0470	.0333	.0126	.0058	.0078	.0013	.0007		0.0003	
36,000			.0518	.0379	.0163	.0084	.0085	.0014	.0007		.0003	0.0005
37,000			.0570	.0415	.0186	.0106	.0093	.0014	.0008		.0005	.0005
38,000			.0630	.0456	.0209	.0141	.0108	.0015	.0009		.0009	.0005
39,000			.0688	.0481	.0238	.0164	.0128	.0018	.0009		.0009	.0005
40,000			.0760	.0537	.0269	.0188	.0140	.0019	.0009		.0009	.0005
41,000			.0838	.0601	.0309	.0210	.0150	.0021	.0010		.0009	.0005
42,000			.0915	.0658	.0348	.0243	.0170	.0021	.0012	0.0007	.0011	.0005
43,000			0.0987	.0714	.0370	.0273	.0185	.0024	.0013	.0007	.0011	.0005
44,000				.0789	.0451	.0298	.0210	.0026	.0013	.0009	.0011	.0010
45,000				.0856	.0494	.0325	.0230	.0028	.0013	.0009	.0011	.0010
46,000				.0939	.0558	.0349	.0258	.0031	.0013	.0009	.0014	.0010
47,000				.1023	.0615	.0389	.0270	.0040	.0015	.0009	.0014	.0010
48,000				.1117	.0680	.0427	.0300	.0044	.0016	.0009	.0014	.0010
49,000				.1217	.0742	.0452	.0320	.0054	.0017	.0011	.0014	.0010
50,000				.1333	.0820	.0493	.0358	.0063	.0022	.0011	.0014	.0010
51,000				.1428	.0922	.0535	.0373	.0068	.0025	.0013	.0017	.0010
52,000				0.1525	.0980	.0570	.0408	.0086	.0030	.0013	.0017	.0010
53,000					.1074	.0610	.0458	.0096	.0042	.0013	.0017	.0010
54,000					.1175	.0656	.0485	.0114	.0053	.0013	.0021	.0010
55,000					.1265	.0695	.0530	.0131	.0073	.0015	.0021	.0015
56,000					.1356	.0740	.0558	.0155	.0084	.0016	.0023	.0015
57,000					.1456	.0783	.0600	.0179	.0110	.0018	.0025	.0015
58,000					0.1569	0.0830	0.0630	0.0204	0.0138	0.0019	0.0025	0.0015

* Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

TABLE II—*Continued*

Load in Pounds*	Tallow	Lead	Copper	Rocks Employed								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble, ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
59,000	...	...	...	...	...	0.0887	0.0658	0.0235	0.0175	0.0019	0.0028	0.0020
60,000	...	...	...	...	...	.0952	.0690	.0256	.0204	.0020	.0030	.0021
61,000	...	...	...	...	...	.1012	.0728	.0300	.0237	.0023	.0030	.0023
62,000	...	...	...	...	...	.1060	.0765	.0336	.0274	.0025	.0034	.0024
63,000	...	...	...	...	...	.1115	.0825	.0370	.0312	.0029	.0038	.0024
64,000	...	...	...	...	...	.1168	.0865	.0410	.0339	.0030	.0040	.0026
65,000	...	...	...	...	...	.1223	.0900	.0450	.0380	.0030	.0043	.0027
66,000	...	...	...	...	...	.1278	.0938	.0496	.0424	.0035	.0048	.0028
67,000	...	...	...	...	...	.1330	.1013	.0544	.0466	.0035	.0050	.0031
68,000	...	...	...	...	...	.1378	.1055	.0588†	.0506	.0039	.0052	.0031
69,000	...	...	...	...	...	.1445	.1103	.0646†	.0550	.0040	.0056	.0034
70,000	...	...	...	...	...	.1498	.1155	.0681	.0585	.0041	.0056	.0035
71,000	...	...	...	...	...	0.1553	.1205	.0719	.0649	.0046	.0066	.0036
72,000	...	...	...	...	...	...	.1253	.0761	.0697	.0050	.0073	.0036
73,000	...	...	...	...	...	...	.1270	.0810	.0760	.0050	.0083	.0037
74,000	...	...	...	...	...	...	.1353	.0858	.0806	.0056	.0090	.0039
75,000	...	...	...	...	...	...	.1400	.0909	.0844	.0060	.0096	.0041
76,000	...	...	...	...	...	...	.1441	.0964	.0900	.0135	.0105	.0043
77,000	...	...	...	...	...	...	.1488	.1025	.0960	.0226	.0115	.0048
78,000	...	...	...	...	...	...	.1540	.1080	.1017	.0273	.0129	.0052
79,000	...	...	...	...	...	...	.1583	.1131	.1059	.0300	.0139	.0055
80,000	...	...	...	...	...	...	.1635	.1174	.1139	.0356	.0149	.0058
81,000	...	...	...	...	...	...	.1685	.1229	.1194	.0525	.0176	.0065
82,000	...	...	...	...	...	...	0.1738	.1290	.1247	.0609	.0199	.0072

83,000								.1365	.1298	.0675	.0223	.0079
84,000								.1428	.1373	.0748	.0255	.0087
85,000								.1476	.1438	.0814	.0288	.0098
86,000								0.1543	0.1495	.0894	.0351	.0117
87,000										.0970	.0420	.0136
88,000										.1053	.0484	.0159
89,000										.1120	.0575	.0183
90,000										.1194	.0609	.0213
91,000										.1263	.0678	.0249
92,000										.1320	.0739	.0308
93,000										0.1407	.0808	.0341
94,000											.0864	.0402
95,000											.0928	.0444
96,000											.0987	.0493
97,000											.1067	.0548
98,000											.1133	0607
99,000											.1198	.0651
100,000											.1277	.0718
101,000											0.1349	.0793
102,000												.0859
103,000												.0896
104,000												.0978
105,000												.1048
106,000												.1106
107,000												.1170
108,000												0.1231
Number of experiments performed	2	2	3	5	2	2	3	3	3	2	2	4
Average duration of each experiment	1 hr. 4 min.	1 hr. 20 min.	2 hr. 3 min.	3 hr. 1 min.	3 hr. 32 min.	5 hr. 36 min.	6 hr. 0 min.	5 hr. 26 min.	4 hr. 39 min.	4 hr. 23 min.	5 hr. 14 min.	5 hr. 9 min.

* Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

† Between the daggers in the column pertaining to Dolomite the results are irregular because in one of the experiments the load was removed and when later restored a slight impact was delivered to the deforming rock column.

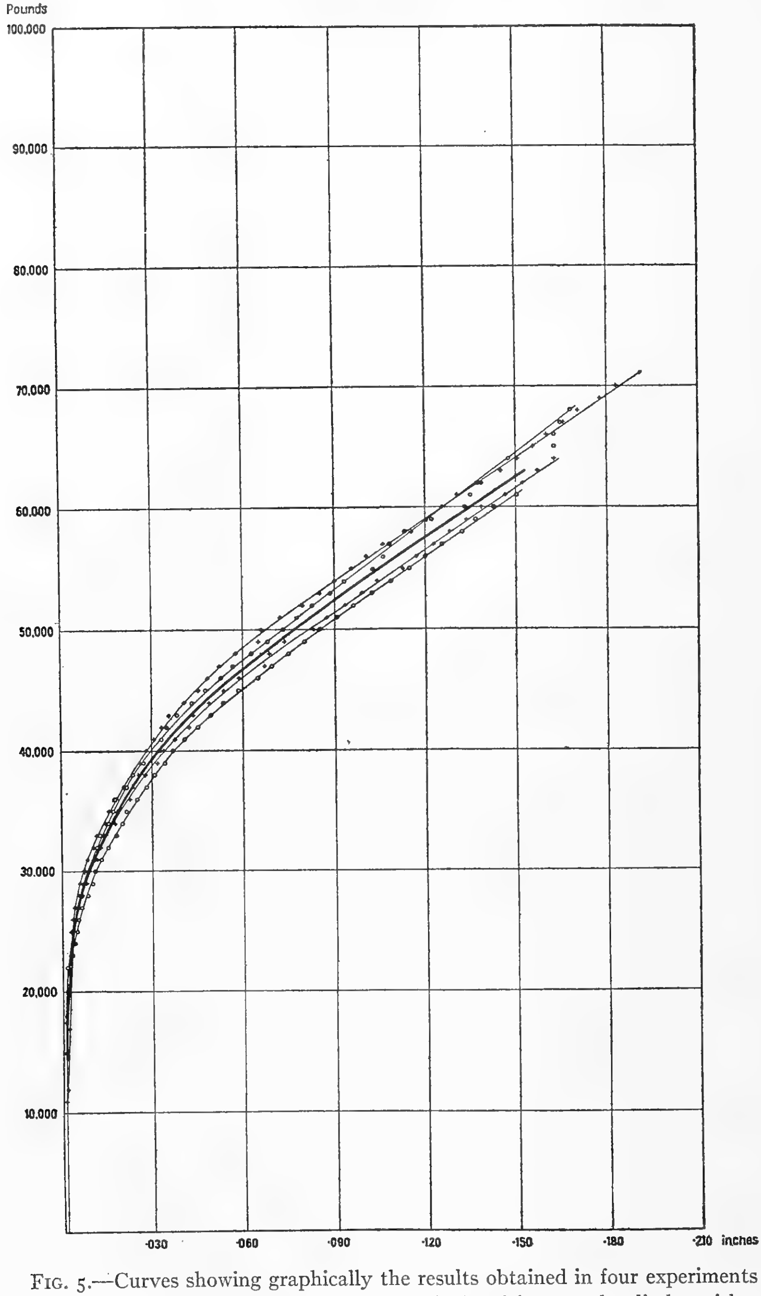


FIG. 5.—Curves showing graphically the results obtained in four experiments on the deformation of Carrara marble when it is inclosed in a steel cylinder with wall 0.25 cm. thick—also the mean of these curves (in heavy line).

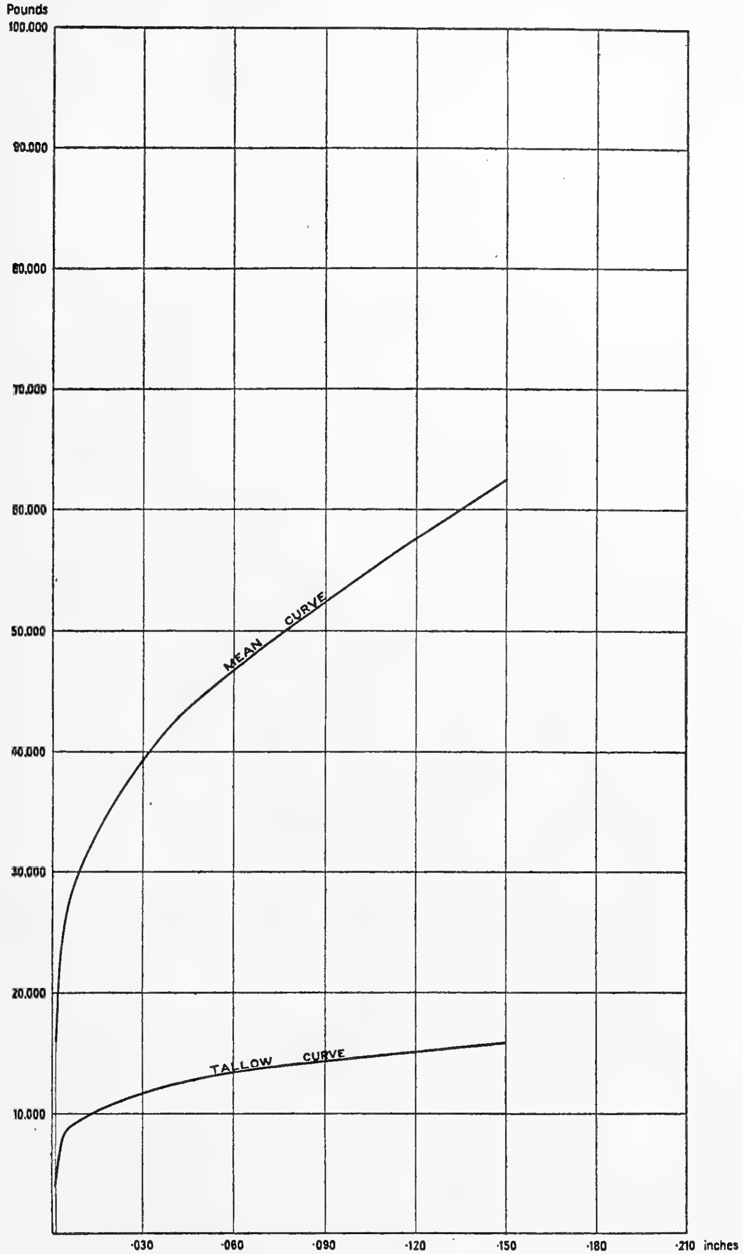


FIG. 6.—The mean of the curves obtained in the deformation of Carrara marble (see Fig. 5) when it is inclosed in a steel cylinder with wall 0.25 cm. thick—with the curve obtained when a steel tube of identical dimensions is deformed when filled with tallow.

Such being the case, with the information thus secured it is possible to separate the two components of the load, namely, that necessary to overcome the resistance offered by the tube and that required to effect the deformation of the marble. If at a series of points the load required to produce a certain distension or bulge in the steel tube when filled with the tallow is subtracted from the load required to produce the same bulge in the case of the tube containing the marble, values are obtained which represent that portion of the load which is expended in affecting the deformation of the marble. This may be termed the *true curve*, and that obtained for a standard column of Carrara marble deformed in a standard steel tube having a wall thickness of 0.25 centimeter is shown in Fig. 7. In the same manner the *true curve* for each of the other rocks may be plotted from the data presented in Tables I and II. It will be seen that, in the case of Carrara marble, this curve starting from a distension of 0.001, which may be considered to be due to elastic deformation, and which is produced by a load of 12,000 pounds, shows a rapid deflection to a point representing a distension of 0.052 which is produced by a load of 33,000 pounds, after which it develops into what is practically a straight line until the tube ruptures.

This shows that after the elastic limit of the marble has been passed, at about 12,000 pounds, and the marble commences to deform, the load which is required to start this movement and produce a unit of diametral expansion is relatively great. As the movement progresses the additional increment of load required to produce a unit of diametral expansion grows progressively less till a bulge of 0.052 is reached, after which there is a definite and constant ratio between the increase of load and the expansion which it produces. This ratio is 0.0065 for each increase of 1,000 pounds in load.

It will be noted that in the case of the slate, just after the rock began to deform, the curve shows a sudden break or sag which is repeated at a second point before the regular movement, indicated by the nearly straight line, is developed. This is due to the fact, above mentioned, that the slate, being a foliated and not a granular rock, is not isotropic in its response to pressure. It consists of little

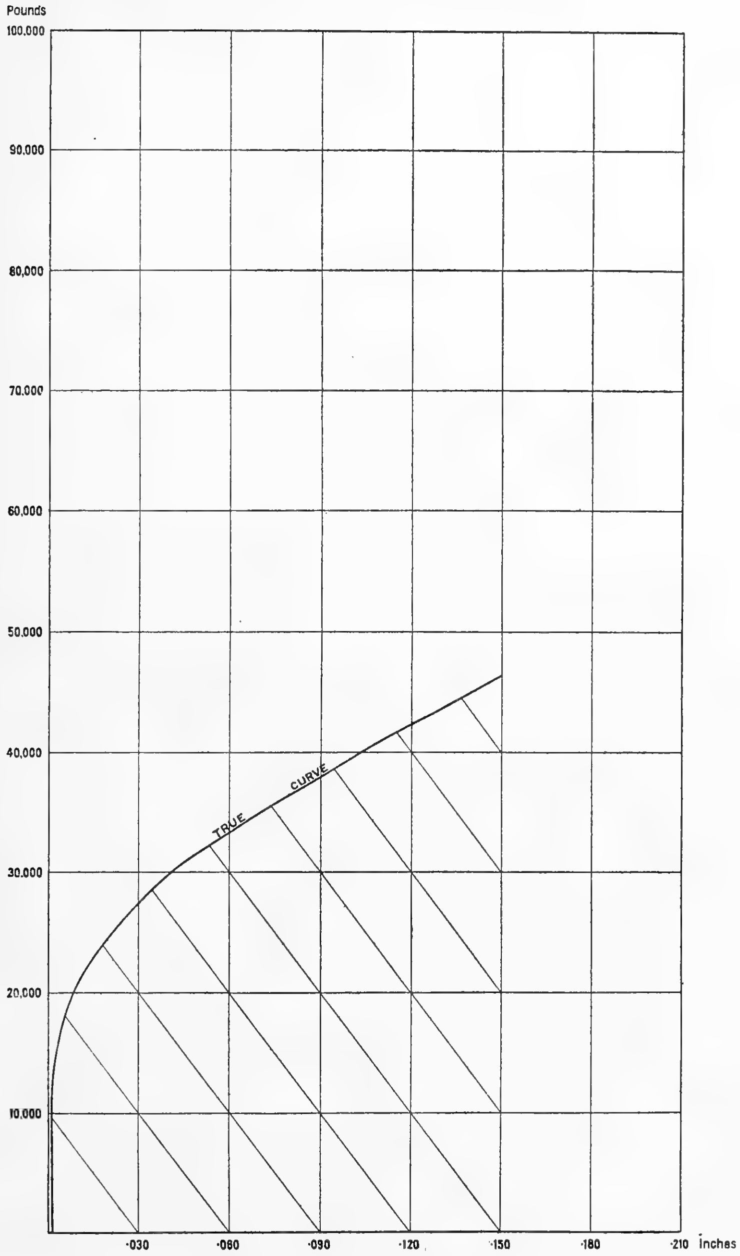


FIG. 7.—True curve obtained by the deformation of a standard column of Carrara marble in steel cylinder with wall 0.25 cm. thick. The area designated by oblique lines represents the work done in effecting the deformation of the marble to a bulge of 0.150 inch.

plates of kaolin and muscovite lying parallel to one another and at right angles to the direction in which the pressure is exerted. The breaking down of the foliated structure of the rock is indicated on the curves by the irregularities to which reference has been made.

It will also be seen that in the case of granite, when the lateral resistance is relatively low (e.g., when the rock is inclosed in the steel tube having a 0.25-centimeter wall), there is at the same point a sag, though much less marked, due to the fact that the lateral resistance offered by the tube is not quite sufficient to develop a uniform movement in this the strongest of all the rocks employed in the investigation.

Attention must be drawn to the manner in which deformation goes forward in a column of rock when deformed under the conditions of the experiment. As may be seen, if the tube and the inclosed rock are sawed in two vertically, the column of rock begins to move or flow at the middle, the motion taking place first along the well-known shearing cones, having an angle of approximately 45° (usually somewhat greater), seen when a column or cube of the rock is crushed between the faces of a testing machine in the ordinary determinations of the strength of rock for building purposes. Thus, as the movement progresses, there develops within the column two obtuse cones, having as their bases the faces of the advancing pistons and consisting of portions of the rock which show no evidences whatsoever of deformation, but which are, under the conditions of the experiment, subjected only to cubic compression. As the experiment progresses, these cones (see *A* and *B* in Fig. 8) advance into the deforming rock, additional amounts of the rock shearing off the surfaces of the cones and thus coming to participate in the movements which are going forward. Owing to the fact, therefore, that the quantity of flowing rock is continually increasing in an unknown ratio, it is impossible from the data mentioned above to determine whether the definite increase in the ratio of load to deformation is due to an increase of internal friction developed with increase of pressure, or to the increased amount of material which is being moved.

The answer to this question is obtained from another series of experiments which exactly duplicated those with the columns of

Carrara marble, described above, except that the lateral resistance to movement was increased by increasing the thickness of the walls of the steel tube inclosing the marble from a thickness of 0.25 centimeter to 0.33 centimeter. In these the amount of material moved is identical with that in the series of experiments just described, while the internal friction is increased by the increased thickness of the steel tube.

A series of additional experiments were also made to determine the resistance offered by such tubes when filled with soft tallow.

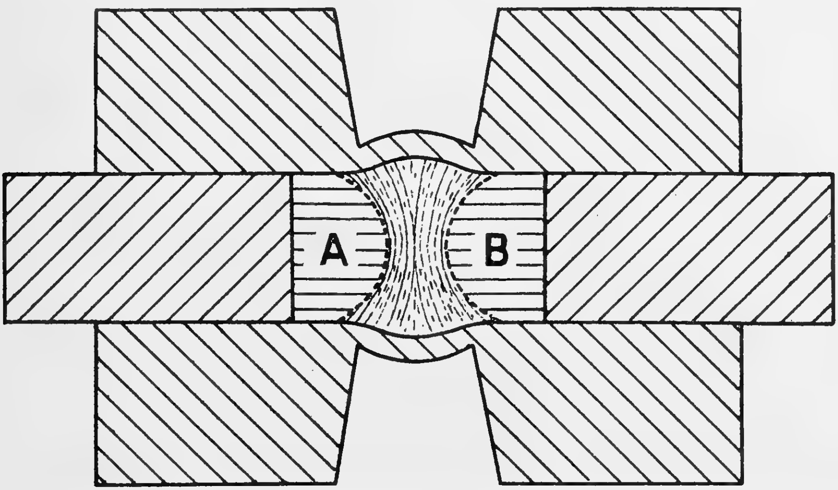


FIG. 8.—Longitudinal section through steel cylinder with pistons inserted and inclosing a deformed column of rock—showing the obtuse shearing cones which advance into the deforming rock.

In this way another series of curves were obtained for each material and another "true curve" for the deformation of a standard column of Carrara marble under conditions identical with those of the former experiments, except that the resistance to deformation offered by the steel tube was much greater. The "true curve" for the deformation of the marble in a steel tube having walls 0.33 centimeter thick is shown in Fig. 10.

An inspection of this curve will show that while, as before, starting from the limit of elastic expansion the rising load at first induces a relatively small amount of movement in the rock, the

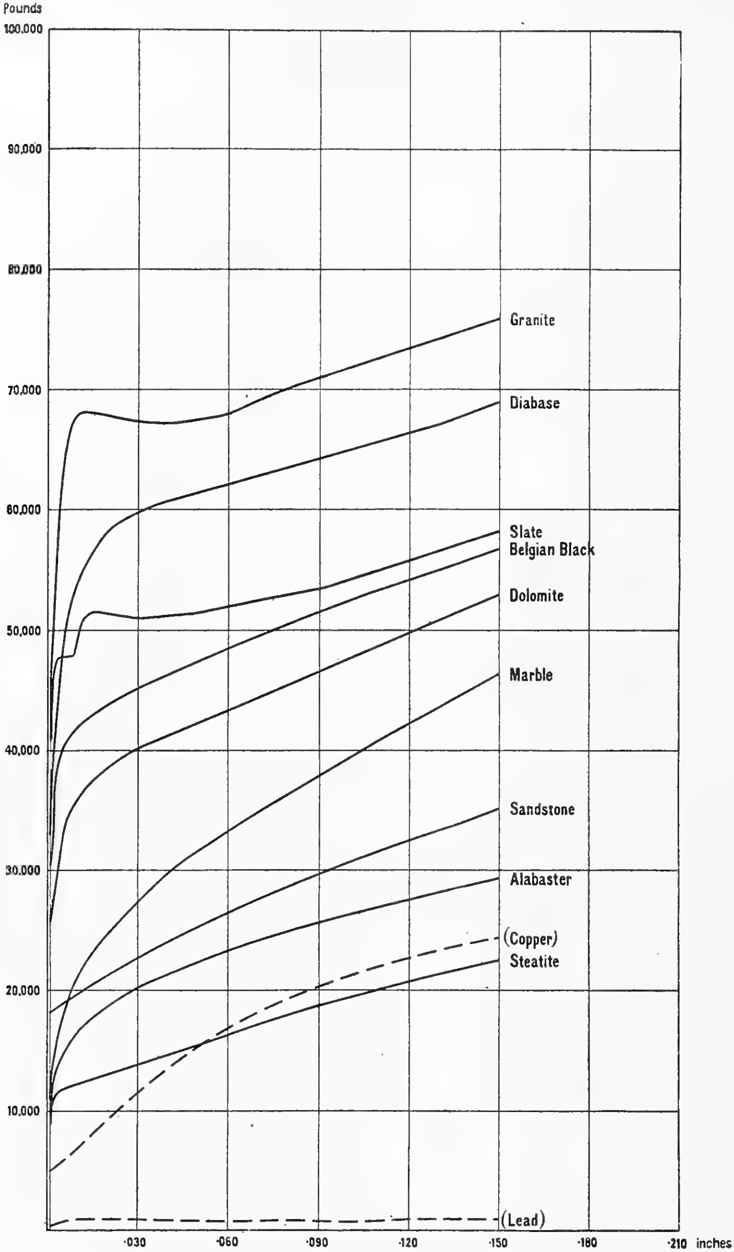


FIG. 9.—True curves obtained by the deformation of the several rocks when inclosed in the steel cylinders with wall 0.25 cm. thick.

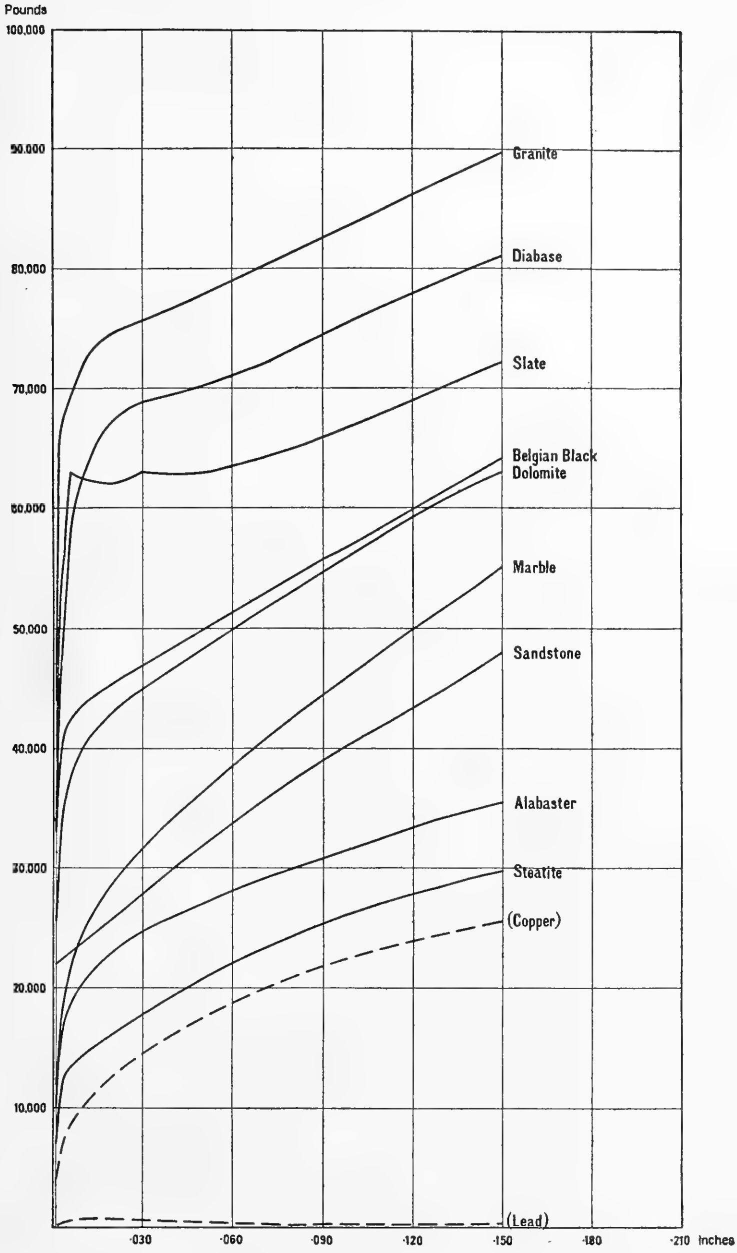


FIG. 10.—True curves obtained by the deformation of the several rocks when inclosed in the steel cylinders with wall 0.33 cm. thick.

ratio of the amount of this movement to increment of loads increases rather rapidly, and, after deformation amounting to about 0.06 has been brought about—which requires a load of 38,750 pounds—the ratio of increase of load to amount of deformation of the column becomes constant, as when the marble is deformed in the tubes with thinner walls. It will be seen, however, that for the experiments in the thicker-walled tube this ratio of increase is much less than when the wall was thinner, i.e., 0.25 centimeter being 0.0051 diametrical increase for each increase of 1,000 pounds in the load, instead of .0065, as in the first series of experiments.

This demonstrates that the moving rock possesses internal friction and that with the increase of the lateral resistance the amount or coefficient of friction rapidly increases, and at a constant ratio.

The investigation was then extended to the other rocks of the series enumerated on pp. 598 and 599. The conditions and method of conducting the experiments were in every case identical with those just described with Carrara marble. Two sets of standard steel tubes, having wall thicknesses of 0.25 centimeter and 0.33 centimeter, respectively, were employed, and the true curves were plotted representing the mean of a series of experiments in each case (see Figs. 9 and 10).

"WORK DONE" IN THE DEFORMATION OF ROCKS

If Px be the load to which the specimen is subjected and Py be the resistance to movement offered by the inclosing walls of the steel cylinder, the data were first examined to ascertain whether the formula

$$Px - Py = \text{a constant}$$

represents the movement, and it was found that this was not the case. They were then studied to see whether each rock possessed a constant factor K, which might be termed its modulus of plasticity, as in the formula

$$Px - KPy = \text{a constant}$$

It was found that, if the data are calculated so as to take into consideration the bulge of the cylinder and are plotted to show

vertical stress as compared with lateral stress, this formula represents the facts and that each of the softer rocks possesses a definite modulus of plasticity, this being also true in the harder rocks in the earlier stages of the deformation at least.

This interesting fact is discussed at length in the accompanying paper by Dr. King, where a mathematical treatment of some of the new data developed in the present investigation is also presented, illuminating certain parts at least of that hitherto unsubdued and almost unoccupied domain—the mathematics of the flow of solids.

In the present paper, without entering into a mathematical treatment of the subject, the following deductions from the experimental data may be indicated.

If a vertical line be drawn cutting off the "true curve" obtained in the case of any rock when the deformation of the tube amounting to 0.15 has been reached, and if the area inclosed by this line, the "true curve" itself, and the base line of the diagram be measured, this area represents the "work done" to effect the deformation of the rock. This area showing the "work done" in deforming a standard column of Carrara marble in a 0.25-centimeter steel tube in Fig. 7 is shaded. In Fig. 9 the "true curves" obtained in this deformation of all the rocks of the series, in steel tubes having a wall thickness of 0.25 centimeter, are shown, and in Fig. 10 the complete series of "true curves" obtained when the wall thickness of the tube is increased to 0.33 centimeter is set forth. In both figures the curves are cut off at the ordinate 0.15, and the area representing the "work done" in the case of each rock is clearly shown and may be compared.

Table III sets forth these comparative values in square inches. This table shows quite clearly that with the increased resistance, offered by the thicker-walled steel tube, the amount of work required to effect an equal deformation increased in the case of every rock. It also sets forth the comparative value of these increases and also the relative amount of work done to deform the different rocks of the series.

The table thus shows that the "work done" in deforming a column of marble of the size employed and under the conditions of the experiment, when inclosed in the thinner-walled tube, is to the "work done" when an identical column is deformed, when inclosed

in the thicker-walled tube, as 51,708 is to 60,415. Or, again, that the "work done" in deforming a marble column, whether the resistance be small or great, is almost exactly one-half of that required to effect an equal amount of deformation in a column of granite under the same conditions. That is to say, almost exactly twice as much work is required to deform granite as is required to effect an equal deformation in the case of marble and nearly four times as much as is required to produce an equal deformation in the case of steatite.

TABLE III

Relative Amount of "Work Done" in Effecting an Equal Deformation in Unit Columns of Different Rocks

	Under Resistance of	
	0.25 cm. Steel Tube	0.33 cm. Steel Tube
Steatite	26,054	34,123
Alabaster	35,569	42,946
Sandstone	41,262	53,446
Marble	51,708	60,415
Dolomite	66,362	77,092
Belgian Black	73,754	79,362
Slate	79,069	97,154
Diabase	92,985	107,431
Granite	104,169	119,877

TABLE IV

Relative Amount of "Work Done" in Effecting an Equal Deformation in Unit Columns of Different Rocks Calculated on the Basis of Marble as Unity

	Under Resistance of	
	0.25 cm. Steel Tube	0.33 cm. Steel Tube
Steatite	0.50	0.56
Alabaster	0.69	0.71
Sandstone	0.80	0.88
Marble	1.00	1.00
Dolomite	1.28	1.28
Belgian Black	1.43	1.31
Slate	1.53	1.61
Diabase	1.80	1.78
Granite	2.01	1.98

If the "work done" to deform marble be taken as unity, these figures may be set forth as in Table IV.

In these tables there is expressed in actual values the phenomena which are displayed in such a striking manner in the great exposures of the Grenville series and in other terranes which have undergone deformation at great depths below the surface of the earth where the same force has acted on a complex of rocks of diverse character. In these occurrences some of these rocks are torn to fragments, which are then carried far apart in a flowing matrix formed of some other and more plastic member of the complex. This is seen in a striking manner where dykes of diabase or belts of granite cut through a limestone, and the whole complex is then deformed under conditions of deep-seated differential pressure. The diabase dyke or belt of granite is torn apart into angular fragments, which are floated along in sinuous curves in the plastic flowing limestone, like logs or drifting timber on the surface of a flowing river (see Fig. 11).

EFFECT OF A CHANGE IN THE RAPIDITY OF THE APPLICATION OF PRESSURE

In Fig. 12 there are two curves: one showing the deformation of alabaster, the other, the deformation of marble. These also illustrate the effects of a change in the rate at which the pressure is applied.

In the former case, after a load of 36,000 pounds had been gradually applied in successive increments and no movement had taken place under the load for 2 minutes, the next increment of load was by mistake applied suddenly, thereby submitting the rock to an impact instead of to a slow increase of pressure. This, as will be seen, produced at once a movement of 0.045 inch. Following this, however, four increments of load, each of 1,000 pounds, had to be applied before the movement was resumed, and two additional increments, each of 1,000 pounds, had to be applied before the movement could be re-established in its regular course, after which the flow continued in the line followed by the normal curve.

In the second case—that of the marble—the normal course of the experiment was interrupted four times by postponing the time of reading the deformation produced by a new increment of load much longer than usual, namely, from 9 to 75 minutes. These were when the load on the column of rock was 40,000, 55,000,

60,000, and 65,000 pounds, respectively. It will be noted that the same effect, though on a smaller scale, was produced as that just described as the result of impact. An abnormal increase of load

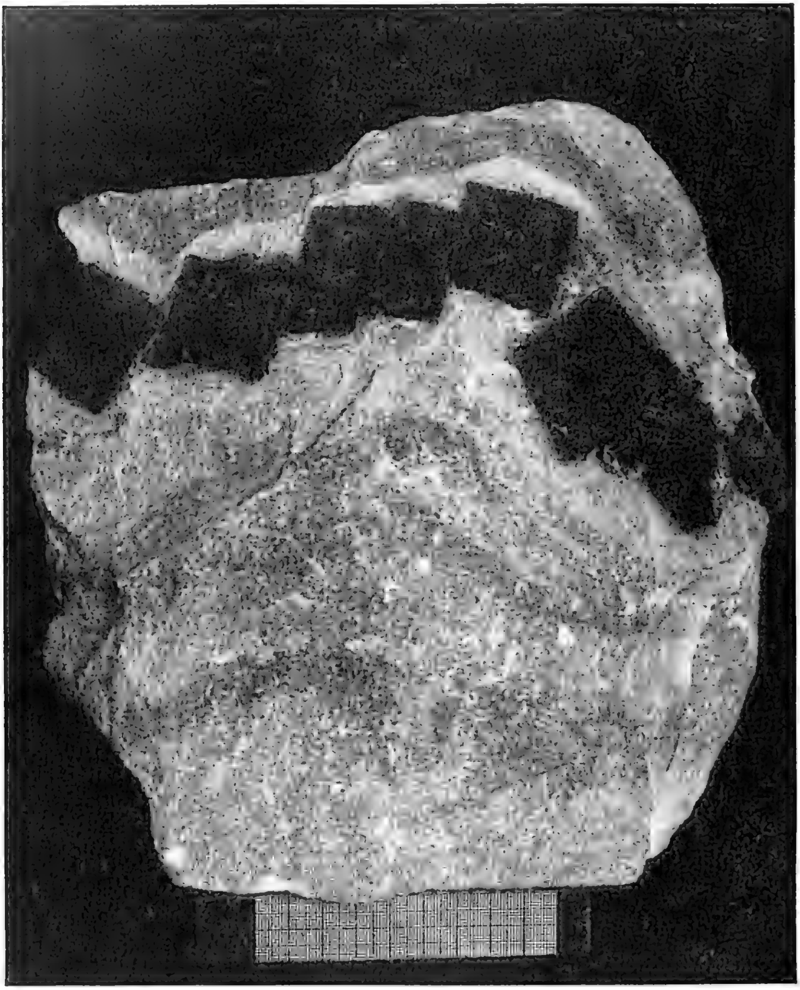


FIG. 11.—Photograph of a specimen of Trenton limestone which has been cut by a narrow dyke of camptonite. The whole has then been distorted by pressure exerted by the intrusion of the igneous mass constituting Mount Royal. The harder camptonite has been broken into fragments which have been carried apart in the flowing mass of more plastic limestone (Canadian Northern Railway Tunnel through Mount Royal, Montreal, Canada).

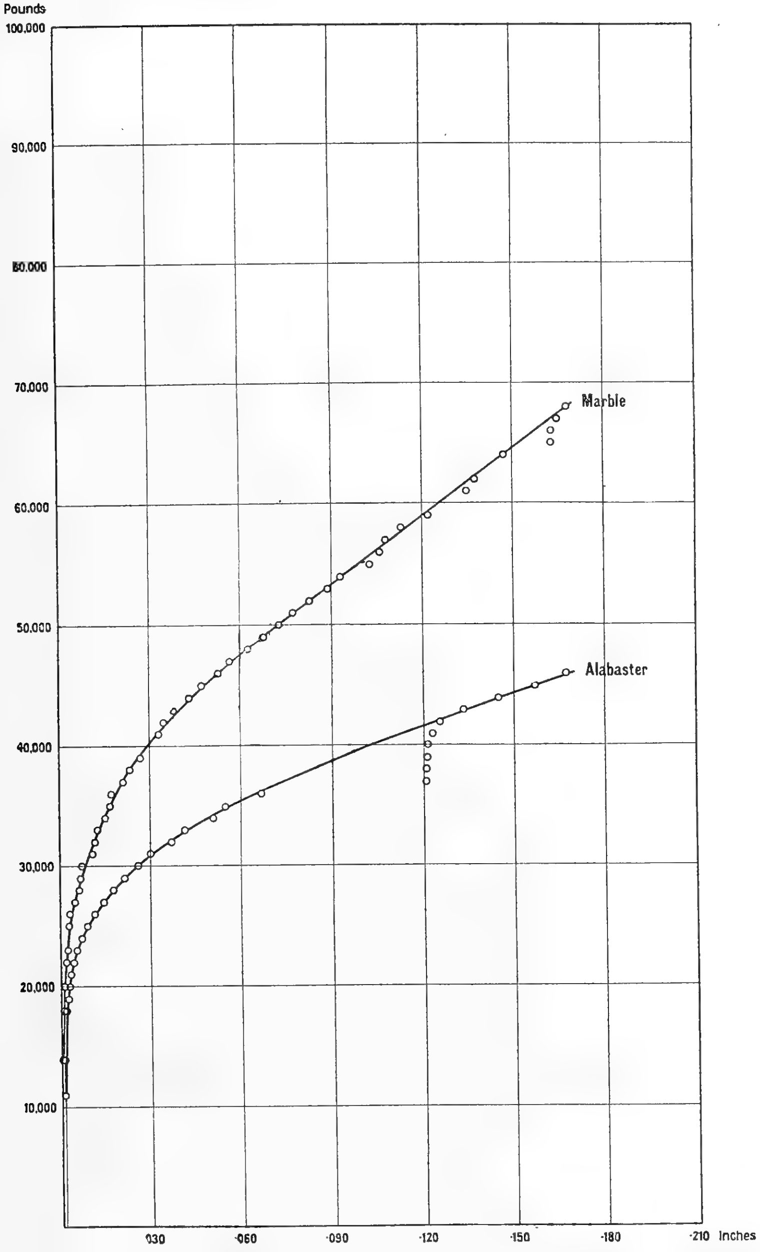


FIG. 12.—Curves showing the effect of change in rate of application of pressure

was required to bring about a re-establishment of the movement, which, however, eventually resumed its former course.

BEARING OF THE RESULTS ON CERTAIN PROBLEMS PRESENTED BY THE EARTH'S CRUST

The experimental results afford a reply to the question propounded by Dr. Gilbert and set forth in the opening paragraph of this paper. They also have a direct bearing on the problems presented by the origin of "decken" and by the theory of isostasy.

When movement producing deformation is once started in the rock under the influence of tangential thrust, resulting in the breaking down of its texture, the rock, if deeply buried in the earth's crust, does not on that account offer a decreased resistance to further movement.

Some experiments by Karman[1] on the deformation of marble under differential pressure have yielded data with reference to the amount of this pressure which must be exerted in the case of marble in order to induce plastic flow in the rock. The data obtained represent maximum results, because in the experiments the pressure was applied rapidly as compared with that which would be developed in any earth movements, and, also, the factor of heat was not taken into account. It must be noted, however, that heat and a very slow application of the deforming force would produce movements under lower pressures than those made use of in the experimental work. Karman found that, if a column of marble were submitted to a supporting or containing pressure, such as that exerted by the steel tube in our experiments, amounting to 685 atmospheres—which would be equivalent to that exerted by the overlying strata at a depth of 2.53 miles below the surface[2]—it would flow uniformly and continuously under a load of 2,870 atmospheres applied to the ends of the column. If the containing pressure fell below the value mentioned, that is, if the rock occupied a position in the earth's crust nearer the surface, it would speedily crumble and break to pieces, presenting in this way a failure similar

[1] "Festigkeits Versuche unter allseitigem Druck," *Zeit. des Ver. deut. Ingenieure*, October 21, 1911.

[2] F. D. Adams, "Depth of the Zone of Flow in the Earth's Crust," *Journal of Geology*, February, 1912.

to that which is obtained in testing building stones in the laboratory. On the other hand, if the containing or supporting pressure is increased, the load required to produce deformation rapidly increases also, and the experiments seem to indicate that with a containing pressure of about 10,000 atmospheres, which would be equivalent to a depth of about 22 miles below the surface, it would be impossible to make the marble flow, except under a pressure which would be simply colossal.

Since with the increase of resistance to tangential thrust, that is, with increasing depth below the surface of the earth, the amount of such thrust required to produce movements in the earth's crust increases rapidly, it is evident that the great movements of adjustment by rock flow or transference of material in the earth's crust from one point to another—other than the transference of rock in a molten condition—must take place comparatively near the surface. That is, beneath the zone of fracture where adjustment takes place by faults and overthrusts—in the zone of flow—movements so far as they are determined by pressure are effected with an ease which increases rapidly in proportion to their nearness to the surface.

It would seem, therefore, that it is in the upper part of the zone of flow only that the great "decken," as, for instance, those which are developed in the Alps, are produced. This explains the fact that in the mountain range in question it is the upper "decken" which have moved more rapidly and have extended farther than the lower "decken," where the rock is under the increased load and is consequently much less plastic.

Since with the increase of depth there is a rapid increase in rigidity of the rocks of the earth's crust, it is not difficult to understand how it is that, while great movements may take place near the surface of the earth in the upper part of the zone of flow, the globe itself is "more rigid than steel or glass."

The experimental work also affords at least a first approximation to the determination of the dimensions of the forces which are required in order to effect deformation in the earth's crust in the case at least of the chief types of rocks which make up the crust in question.

In these measurements it must again be noted that the factor of pressure alone was considered, no account being taken of the element of heat in the crust, which would undoubtedly tend to increase the ease of movement.

In the experiments it has been shown, as mentioned, that the resistance to deformation exerted by the wall of the steel tube gradually increases as the experiment progresses. If, however, the value of the resistance is taken at a point where the regular column shows a diametral increase of 0.05 inch (or 6.35 per cent), i.e., when the deformation is well under way and after which it becomes proportional to the increased tangential pressure, this resistance, in the case of the experiment with the steel wall 0.25 centimeter thick, would be equivalent to 26,685 pounds to the square inch, or 1,815 atmospheres, that is, to a depth of 4.2 miles below the surface.

In the case of our experiment with a steel wall 0.33 centimeter thick it would be equivalent to 37,359 pounds per square inch, or 2,542 atmospheres, that is, to a depth of 5.8 miles below the surface.

Thus at these respective depths the additional tangential thrust required to induce a pronounced movement in the case of marble and granite, respectively, would be as shown in Table V.

TABLE V

	At Depth of 4.2 Miles		At Depth of 5.8 Miles	
	Pounds per Square Inch	Atmospheres	Pounds per Square Inch	Atmospheres
Marble	66,400	4,517	74,500	5,068
Granite	138,500	9,422	159,600	10,857

CONCLUSIONS

1. All the rocks employed in the present investigation can be deformed under differential pressure at ordinary temperatures.

2. In order to effect an equal deformation, it is necessary to employ differential pressures having different values in the case of the several rocks.

3. The ease with which these rocks are deformed has as one of its functions the hardness of the rock (or of the minerals composing it).

4. In the case of the softer rocks—alabaster, steatite, marble, etc.—the deformation is produced by movements due to a slipping within the constituent crystals of the rock on their gliding planes, often accompanied by twinning, the movement in this case being similar to that seen in metals when they are deformed. In the harder rocks the deformation is accompanied by granulation, the texture developed being similar to that found in mylonite.

5. Each of the softer rocks at least has a well-defined modulus of plasticity.

6. The "work done" when a rock is deformed by a tangential thrust, within the earth's crust, increases rapidly with the weight of the superincumbent strata, i.e., with its depth below the surface.

7. The relative ease with which the several rocks will flow under differential pressure is shown in Tables III and IV, which give mathematical expression of the "work done" in deforming standard columns of each rock.

8. A uniform thrust exerted on a prism of the earth's crust may deform and fold the upper portion of the mass, while it will be quite insufficient to produce any movement in the lower part of the same mass.

9. The thrust required to develop deformation, taking no cognizance of the influence of heat or the time effect which might result if the pressure were applied with extreme slowness, in the case of marble, and of granite, is shown by the values given in Table V.

10. To revert to the question propounded by Dr. Gilbert, in order to develop flow in any rock within the earth's crust the rock must be submitted to a differential stress which is greater than that which is required merely to break down its texture and very much greater than that which is sufficient to crush it to pieces under the ordinary conditions which obtain at the surface of the earth.

ON THE MATHEMATICAL THEORY OF THE INTERNAL FRICTION AND LIMITING STRENGTH OF ROCKS UNDER CONDITIONS OF STRESS EXISTING IN THE INTERIOR OF THE EARTH

LOUIS VESSOT KING
McGill University, Montreal

INTRODUCTION

That solid bodies could be permanently deformed and made to flow without rupture under sufficiently great stress has long been known. The extensive experiments of Tresca on the flow of metals[1] (1864–72) directed the attention of several mathematicians of the time to the subject. Tresca announced as a result of his experiments the simple law that a stressed solid would commence to flow as soon as the maximum shearing stress exceeded a limiting value K characteristic of the solid. This hypothesis was incorporated into the elastic solid theory by Saint-Venant[2] and others. The hope was expressed by these writers that by effecting the solution of simple problems in "plasticodynamics," corresponding to the experimental arrangements employed, it might be possible, not only to verify the theoretical results, but also to determine a specific constant K characteristic of the various metals and related in an intimate manner to other physical constants. It was found possible, however, to solve only a very limited number of extremely simple problems: (1) circular cylinder under uniform pressure over the plane ends or subject to uniform lateral pressure; (2) cylindrical shell constrained to remain of constant length and subject to uniform internal and external pressure; (3) circular cylinder twisted beyond the elastic limit; (4) bar of rectangular section bent by a suitable distribution of forces to take the form of a circular arc.

[1] H. Tresca, *Par. Mém. Sav. Etr.*, XX (1872), 75 ff. and 281 ff. A summary of Tresca's experiments is given by L. S. Ware, *Journal of the Franklin Institute*, LXXIII (1877), 418 f.

[2] Saint-Venant, *Comptes Rendus*, LXVII (1868), 131 ff., 203 ff., 278 ff.; LXVIII (1869), 221 ff., 290 ff.

None of these simple problems corresponded, however, to any detailed observations available. The position with regard to the final mathematical interpretation of Tresca's observations was summed up by Saint-Venant in a communication to the French Academy.[1] It was stated that, before much progress could be made in formulating a mathematical theory of plastic flow, it would be necessary to plan experiments more easily capable of mathematical specifications; in particular he recommended that means be taken to trace out in the *interior* of the solid the extent of the plastic deformations. The difficulty of doing this without at the same time interfering with the continuity of the solid under test has apparently not been overcome up to the present, so that data on plastic deformation available for mathematical treatment are still very meager.

It is interesting to notice, however, that we have available at the present day a method of exploring the internal structure of solids which seems to fulfil the need expressed by Saint-Venant. By the use of extremely powerful X-rays it has been found possible to detect internal cavities in steel castings not visible on the surface. The subject has recently been extensively studied by Davey,[2] who states that it is possible to detect an air-inclusion 0.021 inch thick in $1\frac{1}{4}$ inches of steel and an air-inclusion 0.007 inch thick in $\frac{5}{8}$ inch of steel. More recently Pilon,[3] making use of the Coolidge tube, has successfully penetrated 5.5 centimeters of steel. This method appears to the writer to offer the means of studying in successive stages the plastic deformation of specimens of various materials under conditions of intense stress. In these circumstances it would be necessary only to drill extremely fine holes in the specimen in various directions and to study the deformation of these as the solid is made to flow.

Tresca's hypothesis that flow in a solid commences and continues as long as the shearing stress exceeds a definite limit has been found

[1] Saint-Venant, "De la suite qu'il serait nécessaire de donner aux recherches expérimentales de plasticodynamique," *Comptes Rendus*, LXXXI (juillet, 1875), 115–21.

[2] W. P. Davey, *Trans. Am. Electrochem. Soc.*, XXVIII (1915), 407–18.

[3] H. Pilon, *Rev. de Mét.*, XII (Nov., 1915), 1017–23.

by later tests to be only approximately true. It is found that to produce continuous flow in a plastic solid it is necessary continuously to increase the distorting stress. A simple illustration of this fact is to be noticed in the manner in which a short circular cylinder crushed in a testing machine ultimately breaks down. According to Tresca's theory the surfaces of shear should be cones of semi-vertical angle of 45°, while experiments indicate that the angle is more often in the neighborhood of 55° for a material like cast iron.[1] These results have led to a modification of Tresca's hypothesis as already mentioned. The effect of this so-called "resistance to flow" does not appear to have been studied with a view to formulating the laws according to which solids may be made to flow continuously.

In the field of experimental ballistics the use of the permanent deformation of short copper cylinders to measure the enormously high pressures involved in testing explosives by means of the so-called "crusher-gauge," invented by Noble about 1875,[2] has led to the detailed study of the relation of applied stress and deformation produced in these special circumstances.[3] The results of these observations have recently been studied in detail by Brillouin.[4] The behavior of copper shows the existence of internal friction analagous to that observed by Adams and Bancroft in the case of various rock specimens.

In the experiments carried out by the latter investigators the use of nickel-steel jackets of standard thickness to incase the rock specimens subjected to flow is analagous to the use of short cylinders of annealed copper in the crusher-gauges just referred to. In order to obtain the lateral pressure on the specimen corresponding to a given deformation of the nickel-steel jacket, a calibration-curve is obtained by filling the cylinders with tallow. The hydrostatic pressures required to give a series of deformations give the required

[1] A. Morley, *Strength of Materials* (Longmans, Green, & Co., 1908), p. 55.

[2] See *Encyclopaedia Britannica*, 11th ed., article on "Ballistics," for a brief description of the crusher-gauge.

[3] Vieille, *Mémorial des poudres et salpêtres* (Gauthier-Villars, Paris), V, 12–61.

[4] M. Brillouin, "Les grandes déformations du cuivre par écrasement et par traction," *Ann. de Chimie et de Physique*, 9[e] série, II (1914), 489–96.

calibration-curve, just as the copper cylinders of the crusher-gauge are calibrated under known end pressures in a testing machine.

MATHEMATICAL DISCUSSION OF THE OBSERVATIONS OF ADAMS AND BANCROFT DURING THE ELASTIC STAGE

Although the experiments which form the subject of the present discussion were all carried out when both rock and nickel-steel had been deformed beyond the elastic limit, it is not without interest, especially in view of further experiments on the subject, to follow out the distribution of stresses in the rock specimen and in the nickel-steel throughout the elastic stage. The necessary theory from which the formulas given below are derived has been given by the writer in a previous paper.[1] As in that discussion, it is sufficient for the present purpose to consider the ideal problem of plane stress, that is, one in which the end pressures and lateral pressures are such that the displacements at the outer surfaces, both of the rock specimen and of the nickel-steel jackets, are everywhere symmetrical with respect to the axis and everywhere constant for a given load. In reality the nickel-steel jacket shows a bulge over the center of the specimen. As long as this is not too great the analysis will give an approximate representation of the state of stress in the central portion of the specimen and nickel-steel jacket at which the measurements of displacement were taken by means of a sensitive extensometer. The justification for this mode of treatment has already been noticed in the writer's paper previously referred to in its application to a similar problem.

We denote by $\widehat{rr}$ the stress component along the radius r; by $\widehat{\theta\theta}$, the component at right angles to r; and by $\widehat{zz}$, that along the axis. According to Lamé's notation, μ is the modulus of rigidity of the rock specimen and λ one of the moduli of elasticity such that $\kappa=(\lambda+\frac{2}{3}\mu)$ is the modulus of compression. Poisson's ratio is denoted by $\sigma=\frac{1}{2}\lambda/(\lambda+\mu)$. We denote by accented symbols the corresponding elastic constants for nickel-steel. In the problem under discussion we denote by b the radius of the rock specimen and

[1] L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *Journal of Geology*, XX (February–March, 1912), 121–26.

the interior radius of the nickel-steel jacket, and by c the exterior radius of the nickel-steel jacket. If P is the pressure per unit area applied to the end of the test specimen, we have $\widehat{zz}=-P$. The principal shearing stresses are one-half the algebraic difference of the principal stresses and are at once obtained by writing $a=0$ in the equations (13) of the writer's paper mentioned above. We then obtain

$$\left.\begin{array}{ll}\text{(i)} & \tfrac{1}{2}\,|\,\widehat{rr}-\widehat{zz}\,|=\tfrac{1}{2}\,\dfrac{\sigma}{1-\sigma}\,P\left\{\dfrac{1-2\sigma}{\sigma}+\dfrac{\beta}{1+\beta}\right\} \\ \text{(ii)} & \tfrac{1}{2}\,|\,\widehat{rr}-\widehat{\theta\theta}\,|=0 \\ \text{(iii)} & \tfrac{1}{2}\,|\,\widehat{\theta\theta}-\widehat{zz}\,|=\tfrac{1}{2}\,\dfrac{\sigma}{1-\sigma}\,P\left\{\dfrac{1-2\sigma}{\sigma}+\dfrac{\beta}{1+\beta}\right\}\end{array}\right\} \tag{1}$$

where

$$\beta=\frac{1+\sigma}{1-\sigma}\cdot\frac{\mu}{\mu'}\left\{1+\frac{1-\sigma'}{1+\sigma'}\,\frac{b^2}{c^2}\right\}\cdot\frac{1}{1-b^2/c^2} \tag{2}$$

The radial displacement U at the outer surface of the rock specimen is given by

$$\frac{U}{b}=\frac{P}{2\mu}\cdot\frac{\sigma}{1+\sigma}\,\frac{\beta}{1+\beta} \tag{3}$$

Each of the principal shearing stresses (i), (ii), (iii), is associated with a family of surfaces along which the material will crack or flow. These are illustrated in Fig. 1, reproduced from the writer's paper already mentioned. It is important to notice in the present connection that the principal shearing stresses in the interior of the rock, as given by (i) and (iii), are independent of the radius r and remain equal throughout the elastic régime. It thus follows from Tresca's theory that the rock, when stressed under these ideal conditions, will commence to break down or flow *simultaneously* throughout its entire volume. The surfaces of shear which will be associated with the elastic breakdown may either be the system of cones (i) of semivertical angle 45° or the system of helicoidal surfaces (iii) of 45° pitch giving rise to the well-known Luder's lines on the curved surface of the specimen. The particular surfaces of shear which will be observed in any particular test will depend on accidental circumstances, as either system is equally likely to occur.

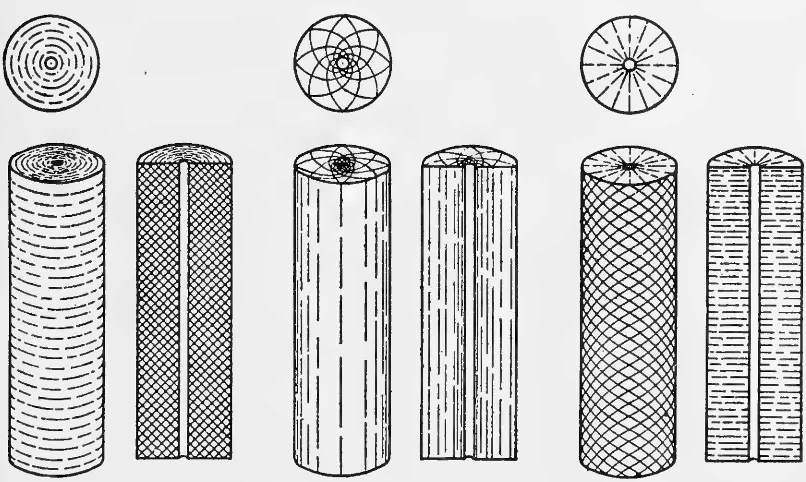
We easily derive expressions for the principal shearing stresses in the nickel-steel jacket. At points distant r' from the axis these are

$$\left.\begin{array}{ll}
\text{(i)}' & \tfrac{1}{2}\,|\,\widehat{rr}'-\widehat{zz}'\,| = \tfrac{1}{2}P\cdot\dfrac{\sigma}{1-\sigma}\cdot\dfrac{1}{1+\beta}\,\dfrac{c^2/r'^2-1}{c^2/b^2-1} \\[2ex]
\text{(ii)}' & \tfrac{1}{2}\,|\,\widehat{rr}'-\widehat{\theta\theta}'\,| = P\dfrac{\sigma}{1-\sigma}\,\dfrac{1}{1+\beta}\,\dfrac{c^2/r'^2}{c^2/b^2-1} \\[2ex]
\text{(iii)}' & \tfrac{1}{2}\,|\,\widehat{\theta\theta}'-\widehat{zz}'\,| = \tfrac{1}{2}P\,\dfrac{\sigma}{1-\sigma}\,\dfrac{1}{1+\beta}\,\dfrac{c^2r'^2+1}{c^2/b^2-1}
\end{array}\right\} \quad (4)$$

The radial displacement U' at the outer surface of the nickel-stee jacket is given by

$$\frac{U'}{c}=\frac{P}{\mu'}\cdot\frac{b^2}{c^2}\cdot\frac{1}{1-b^2/c^2}\cdot\frac{1'}{1+\sigma'} \quad (5)$$

By writing $\mu=0$ and therefore $\beta=0$, $\sigma=\frac{1}{2}$, the foregoing give the familiar results for stresses in a cylinder subject to internal hydro-



(i) (ii) (iii)

FIG. 1.—(Figure from this Journal, Vol. XX, No. 2 [February-March, 1912], p. 123.)

static pressure. The three principal shearing stresses given above all take their maximum value (independent of sign) at the interior

surface $r=b$, and of these maxima (ii)$'$ is the greatest. The maximum shearing stress is therefore

$$\tfrac{1}{2}\,|\,\widehat{rr'}-\widehat{\theta\theta'}\,|_{max.}=P\frac{\sigma}{1-\sigma}\cdot\frac{1}{1+\beta}\cdot\frac{1}{1-b^2/c^2} \qquad (6)$$

It follows from this discussion that elastic breakdown of the nickel-steel jacket commences at the interior surface and, as deformation continues, extends gradually to the outer surface. The surfaces of shear in this case are the system of cylindrical surfaces whose traces on a plane perpendicular to the axis of the cylinder are equiangular spirals intersecting orthogonally and cutting all radii at angles of 45°. An examination of the nickel-steel jackets shows, in fact, that the surfaces of shear approximated roughly to this system. The polished outer surface of stressed specimens showed indications of fine longitudinal ribs, while in such as were actually ruptured it was noticed that the surface of rupture conformed to that predicted from theory. As the rupture occurred when the nickel-steel was stressed very much beyond the elastic limit, the actual surfaces of shear are determined by very complex conditions involving the effect of internal friction, with which we shall deal in a later section.

Numerical results.—A rough verification of the preceding results may be made by calculating the relation between the load and the increase of diameter of the nickel-steel jacket according to equation (5). For nickel-steel we take $\sigma'=0.327$ and $\mu'=10.8\times10^6$ pounds per sq. in., values employed in the writer's paper just referred to. In one set of experiments (referred to as 0.25-centimeter wall) $b=1.00$ cm., $c=1.25$ cm., giving from (2)

$$\beta=3.68\times\frac{1+\sigma}{1-\sigma}\cdot\frac{\mu}{\mu'}.$$

When the jacket is filled with tallow we may take $\sigma=\tfrac{1}{2}$, $\mu=0$, $\beta=0$, so that equation (5) gives

$$U'/c=1.34\times(P/\mu'),$$

or in terms of the total load, $W=\pi b^2P$, we obtain

$$2U'\ (\text{inches})=2.52\times10^{-7}\times W\ (\text{pounds}) \qquad (7)$$

When a specimen of Carrara marble is inserted we have[1] $\sigma=0.2744$, $\mu=3.154\times10^6$ pounds per sq. in., whence $\beta=1.889$ and

$$U'/c=0.176\times(P/\mu'),\text{ or }2U'\text{ (inches)}=3.31\times10^{-8}\times W\text{ (pounds)} \quad (8)$$

In another set of experiments (referred to as 0.33-centimeter wall), $b=1.00$ cm., $c=1.33$ cm., giving

$$\beta=2.96\times\frac{1+\sigma}{1-\sigma}\frac{\mu}{\mu'}.$$

In the case of tallow filling we find as before,

$$U'/c=0.980\times(P/\mu')\text{ or }2U'\text{ (inches)}=1.96\times10^{-7}\times W\text{ (pounds)} \quad (9)$$

and in the case of the Carrara marble specimen

$$U'/c=0.147\times(P/\mu')\text{ or }2U'\text{ (inches)}=2.94\times10^{-8}\times W\text{ (pounds)} \quad (10)$$

In Fig. 2 are compared the observed and theoretical stress-strain diagrams corresponding to the cases calculated out in equations (8) to (10). In the case of tallow filling, the initial slope of the observed curves agrees approximately with the calculated slope. In the case of the marble filling, the agreement is within the limits of error involved in measuring these extremely small strains.

MATHEMATICAL DISCUSSION OF THE OBSERVATIONS OF ADAMS AND BANCROFT DURING THE PLASTIC STAGE

1. *Navier's theory of internal friction.*—Let $\widehat{xx}$, $\widehat{yy}$, and $\widehat{zz}$ be the principal stresses in the solid at a point P measured toward the origin (Fig. 3). Let S be the shearing stress in a plane whose direction cosines with respect to the direction of the three principal stresses are (l, m, n). Let N be the stress normal to this plane. We then have

and

$$\left.\begin{aligned} S^2+N^2&=l^2\widehat{xx}^2+m^2\widehat{yy}^2+n^2\widehat{zz}^2 \\ N&=l^2xx+m^2\widehat{yy}+n^2\widehat{zz} \end{aligned}\right\} \quad (11)$$

Generalizing somewhat on Navier's hypothesis of elastic breakdown, we may state that the material will not break down as long as

$$S<K \quad (12)$$

[1] Adams and Coker, "Elastic Constants of Rocks," *Publication No. 46 of the Carnegie Institution of Washington*, 1906, p. 69.

where K is a function, not only of the stress N normal to the plan at which slide occurs, but also of the previous history of the

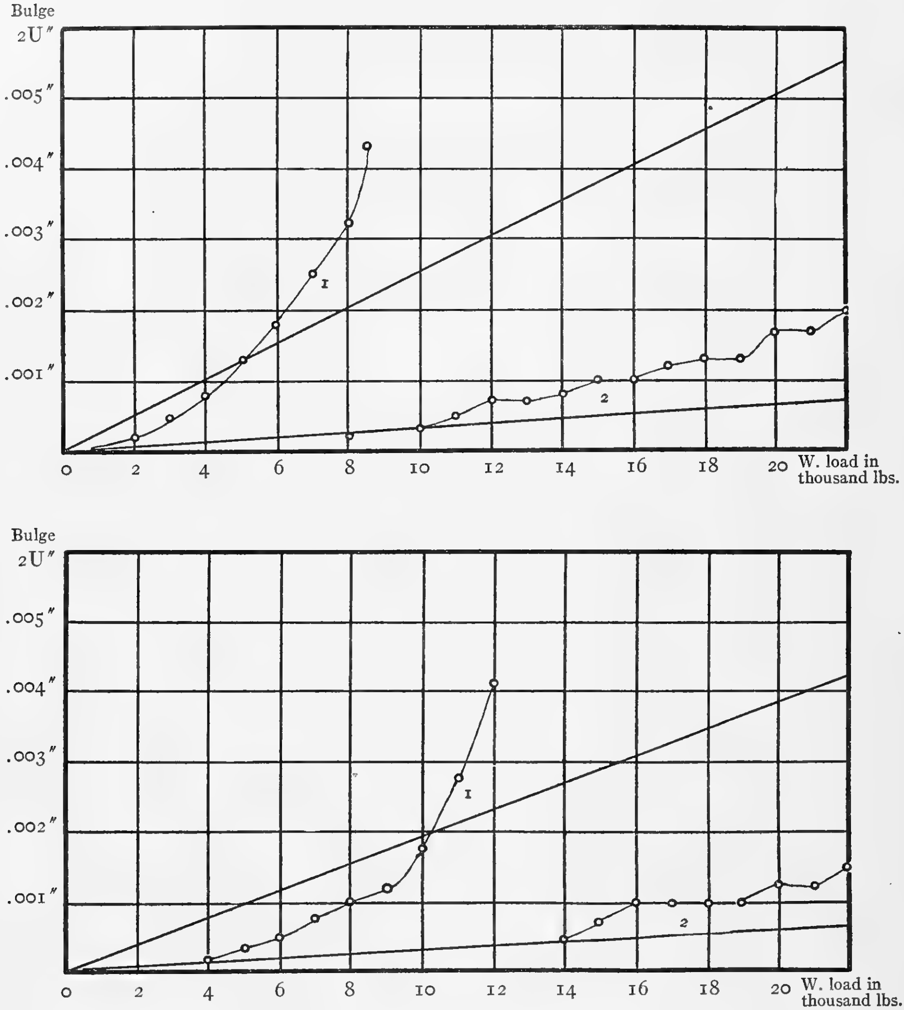


Fig. 2.—Theoretical and observed stress-strain diagrams. Curves 1, tallow filling. Curves 2, Carrara marble filling.

specimen. According to Tresca's hypothesis, K was regarded as a constant, depending only on the nature of the specimen. An exten-

sion of this hypothesis due to Navier (the so-called internal-friction theory) replaces (12) by the condition

$$S<K+\mu N,$$

μ being a new constant somewhat analogous to the coefficient of friction of mechanics. In order to discover the relation between the principal stresses at the elastic limit, it is necessary to find the direction (l, m, n) which makes $(S-\mu N)$ a maximum and equate the result to K. Suppose the principal stresses to be all of the same sign, two of them equal, $\widehat{yy}=\widehat{xx}$, and $\widehat{zz}>\widehat{xx}$ (corresponding to the state of affairs in the cylindrical rock specimens under test). We then have, writing $l=\sin\theta\cos\phi$, $m=\sin\theta\sin\phi$, $n=\cos\theta$,

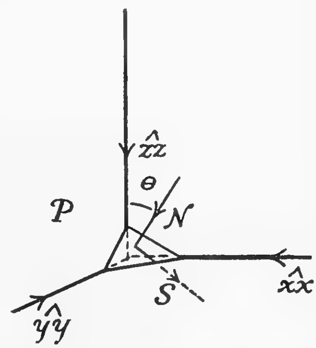


FIG. 3

$$\left.\begin{aligned} S^2+N^2=\widehat{xx}^2\sin^2\theta+\widehat{zz}^2\cos^2\theta,\quad N=\widehat{xx}\sin^2\theta+\widehat{zz}\cos^2\theta \\ S=(\widehat{zz}-\widehat{xx})\sin\theta\cos\theta \end{aligned}\right\} \qquad (13)$$

$$S-\mu N=(\widehat{zz}-\widehat{xx})\sin\theta\cos\theta-\mu(\widehat{xx}\sin\theta+\widehat{zz}\cos^2\theta) \qquad (14)$$

This expression reaches a maximum when

$$\cot 2\theta=-\mu, \qquad (15)$$

in which circumstances

$$(S-\mu N)_{max.}=\tfrac{1}{2}(\widehat{zz}\cot\theta-\widehat{xx}\tan\theta), \qquad (16)$$

and the relation between the principal stresses at breakdown is given by

$$\widehat{zz}=2K\tan\theta+\widehat{xx}\tan^2\theta \qquad (17)$$

where θ is given in terms of μ (the coefficient of friction) by (15). This result indicates that the material in question will break down along a family of cones of semivertical angle $\alpha=\frac{1}{2}\pi-\theta$.

2. *Discussion of observations.*—In the experiments of Adams and Bancroft the cylindrical rock specimens were subjected to end loads transmitted by the steel pistons. As a result of the intense pressure

developed, the rock cylinders were caused to bulge out laterally over the central portion, where the thickness of the nickel-steel jacket was reduced to 0.25 centimeter and 0.33 centimeter, respectively, in the two sets of experiments. The rock was thus subjected to a continuous succession of breakdowns, so that it was possible from these observations to determine the relation between the end and lateral pressures required to keep the rock in movement.

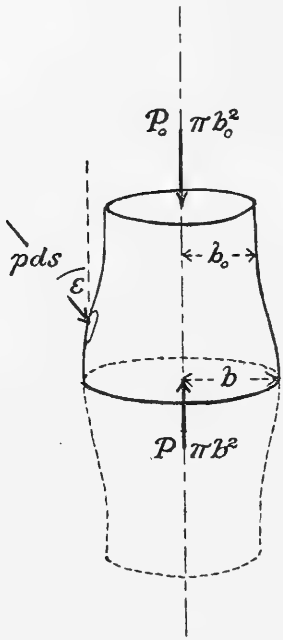


Fig. 4

Considering the central portion of the rock cylinder throughout which the flow takes place, we may reasonably assume, when the bulge is small, that the average pressure-intensity P_0 along the direction of the axis is given by

$$P_0 = W_0/(\pi b_0^2),$$

W_0 being the load on the steel piston and b_0 its radius. As the bulge becomes sensible, it is necessary to make a correction to allow for the increasing area over which the pressure is distributed. Referring to Fig. 4, we denote by P the average pressure-intensity across a plane at right angles to the axis at the position of maximum bulge where the radius of the cross section is b. We denote by p the resultant traction per unit area exerted by the nickel-steel jacket on the rock specimen in a direction making an angle ϵ with the axis. Then, considering the equilibrium of one-half of the rock specimen, we may write

$$\pi P_0 b_0^2 + \int p \cos \epsilon \; dS = \pi b^2 P, \tag{18}$$

the integral representing the total component of the tractions between the rock specimen and the nickel-steel jacket in a direction parallel to the axis of the cylinder. When an exactly similar jacket is filled with tallow and deformed by the application of a load on the steel pistons in the same way, we may consider the pressure in

the interior to be hydrostatic. If p_0 be the hydrostatic pressure required to bulge the nickel-steel jacket to the same radius b, we have instead of (18) the equation

$$\pi p_0 b_0^2 + \int p_0 \cos \epsilon_0 dS = \pi b^2 p_0, \tag{19}$$

where ϵ_0 now denotes the direction which the normal to the deformed surface makes with the axis of the cylinder. It was carefully ascertained in the experiments of Adams and Bancroft that the *shape* of the bulged nickel-steel jacket was the same when occupied by the softer rocks and such an easily flowing metal as lead, in which conditions of pressure approach very nearly to hydrostatic conditions under the very intense loads employed. As the deformation of the nickel-steel jacket is due to the distribution of surface tractions p, it is reasonable to assume that they are distributed in approximately the same way. This is equivalent to asserting that the tangential component of the surface traction between rock and nickel-steel is negligible compared to the normal component, a statement which seems to be reasonable in view of the fact that both rock and nickel-steel are highly polished over the surface of contact. We may thus write $\int p \cos \epsilon \, dS = \int p_0 \cos \epsilon_0 \, dS$ in (18) and (19) and arrive at the relation

$$P = p_0(1 - b_0^2/b^2) + P_0 b_0^2/b^2, \tag{20}$$

giving the average pressure-intensity at the center of the specimen to be identified with $\widehat{zz}$ of equation (17). The corresponding lateral pressure is given by p_0, which is identified with $\widehat{xx}$ of (17).

We are now in a position to test the theory of internal friction expressed by (17) from the observations of Adams and Bancroft. It is only necessary to plot against each other the end pressures $\widehat{zz}$ and the lateral pressures $\widehat{xx}$ as determined above. Such specimens as give straight lines may be said to possess a definite *modulus of plasticity*, K, and *coefficient of internal friction*, μ. Curves obtained in this way are shown in the Appendix, where they are described in detail for the various specimens tested. The results show that for some kinds of rock the curves approximate closely to straight lines between certain limits of pressure. In the interpretation of these curves it must be kept in mind that the material is not broken

down from an initially unstrained state[1] at each stage of the process. The constants of plasticity and internal friction, as determined by the present investigation, refer to rock which is being made to flow continuously. This state of affairs, however, approaches more nearly to that occurring in nature during slow geological deformations than to conditions existing when the rock is broken down from an initially unstrained state.

Under ideal conditions the curves for the observations taken with the nickel-steel jackets of the two wall thicknesses should be identical. Actually, however, they differ to some extent, indicating that the effect of stresses set up by the deformation of the nickel-steel has not been entirely eliminated. The two sets of observations are, however, sufficiently close to give approximate estimates of the relation between the principal stresses which must exist before the rock can be made to flow under conditions existing in the earth's crust. It will be noticed from the curves of Plate I that for the harder rocks, such as diabase and granite, the curves along which breakdown takes place show the existence of a very large coefficient of internal friction. Since the hydrostatic pressure is given by $\frac{1}{3}(2\widehat{xx}+\widehat{zz})$, this is equivalent to the statement that the *stiffness* or limiting shearing stress required to break down the rock increases with the hydrostatic pressure to which the rock is submitted. In other words, we come to the important conclusion that *the stress-difference required to break down rock material under conditions of pressure existing in the earth's crust increases with the depth.* In the application of this result to geophysical problems, the foregoing conclusion may have to be somewhat modified to take into account the rise of temperature with depth. It is highly desirable that further experiments be carried out with a view to ascertaining the influence of this factor.

NOTE ON APPLICATIONS TO GEOPHYSICAL PROBLEMS

Up to the present the only quantitative data available for use in geodynamical problems have been obtained by crushing cubes of various rocks in a testing machine according to the ordinary rules

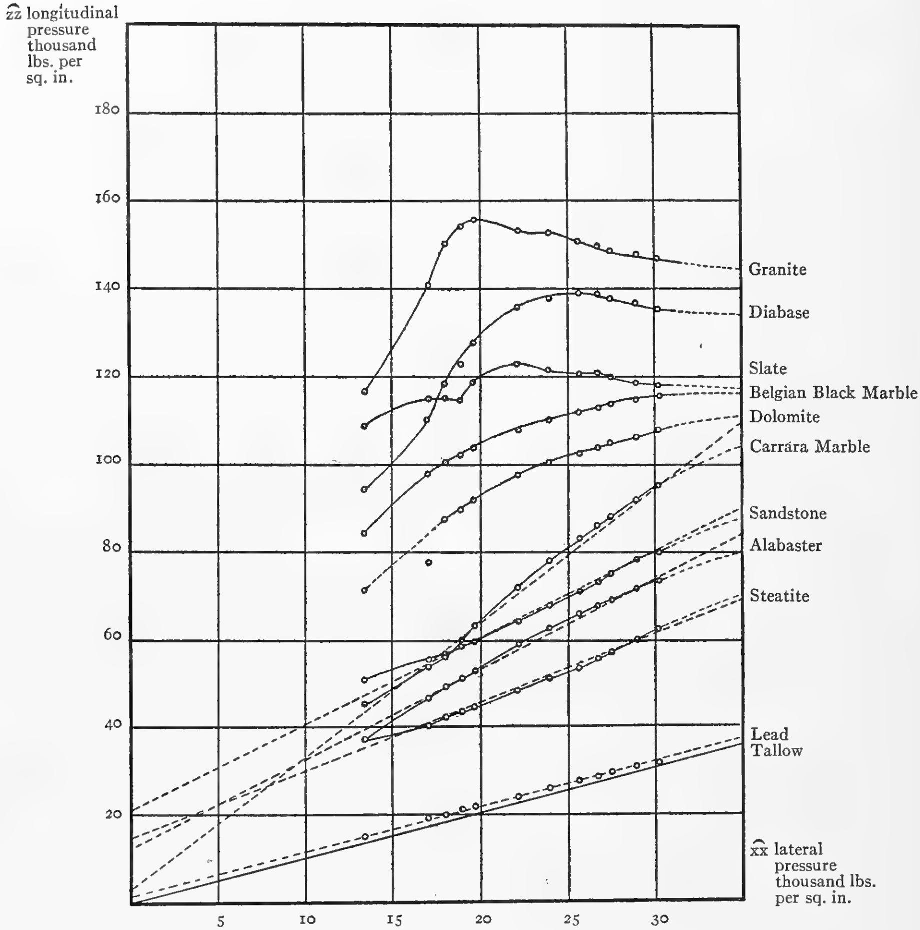
[1] Compare Karman's observations on marble and sandstone, *Zeit. des Vereins deutscher Ingenieure*, October 21, 1911.

of engineering practice. The unsatisfactory nature of such data as applied to conditions of stress deep down in the earth's crust has already been pointed out by the writer.[1] The results now available from the observations of Adams and Bancroft supply much needed data for the purposes of geophysics. Quoting from a classical paper by Sir George Darwin,[2] "With regard to the earth we require to know what is the limiting stress-difference under which a material takes permanent set or begins to flow rather than the stress-difference under which it breaks; for if the materials of the earth were to begin to flow, the continents would sink down, and the sea bottoms rise up." In the paper quoted Darwin estimates roughly the stress-difference in the interior of the earth due to a distribution of continental masses corresponding roughly to the actual distribution. For instance, it is estimated that the stress-difference under the continents of Africa and America is at a maximum at more than 1,100 miles from the earth's surface and amounts to about 4 tons per square inch. Darwin's conclusion that "marble would break under this stress, but that *strong* granite would stand" must be modified considerably in the light of the results of Adams and Bancroft, as the limiting strength of the rock material under the enormous pressure at the depth referred to would probably be increased many times. For the purposes of such calculations the curves of Plate I may be employed as they stand. If, for instance, it is desired to investigate the stability of mountain ranges or of continental elevations, the principal stresses at great depths must be derived from the theory of elasticity, making use of elastic constants derived from the interpretation of seismological records. If the principal stresses at any point be plotted as $\widehat{zz}$ and $\widehat{xx}$ on such a diagram as that of Plate I, a particular rock material will flow if the point falls between the axis $\widehat{zz}$ and the curve characteristic of the particular rock formation under consideration. The material will be on the point of flowing if the point falls on the curve itself, while the rock will stand the stress if the point falls between the

[1] L. V. King, *op. cit.*, p. 120.

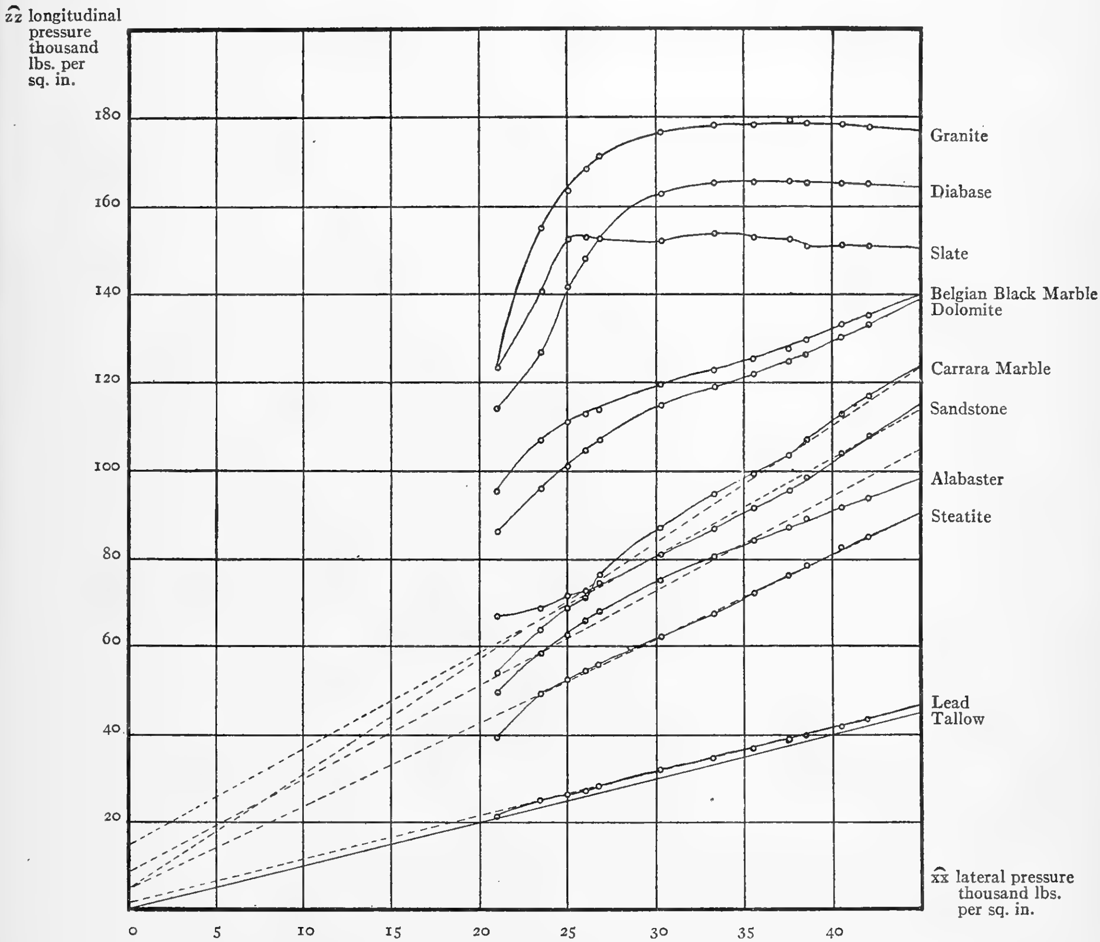
[2] Sir G. Darwin, "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains," *Phil. Trans.*, CLXXIII (1882), 187–230; *Scientific Papers*, II (1908), 495.

PLATE I



RELATIVE PLASTICITIES OF VARIOUS ROCK SPECIMENS
Nickel-steel jackets of 0.25 cm. wall

PLATE II



RELATIVE PLASTICITIES OF VARIOUS ROCK SPECIMENS
Nickel-steel jackets of 0.33 cm. wall

curve and the axis $\widehat{xx}$. Thus for complete stability the entire series of points representing stress-differences beneath a continental elevation must fall in this latter region. It is thus evident that the existing theories of isostasy should, in considering the equilibrium of stresses called into existence by continental elevations and mountain ranges, take account of a "*compensation* of *plasticity*"—i.e., of the increased stiffness or resistance to deformation—of the underlying rock when submitted to greater hydrostatic pressure. With the reservation already made as to the possible influence of temperature, we have a considerable basis of evidence in favor of the conclusion that at any time in the past history of the earth continental elevations might have attained much greater altitudes above sea-level than any at present existing, without giving rise to stress-differences in the earth's interior sufficiently great to have caused rupture or breakdown, owing to the much increased "resistance to flow" set up in the rock material by the great pressure of the overlying crust. We should conclude also that, in the event of flow occurring, the region of flow would be confined to a region of the earth's crust comparatively near the earth's surface. The increasing limiting stress, with pressure characteristic of rock material made to flow as in Adams' and Bancroft's experiments, leads one to the conclusion that great movements of the earth's crust have for the most part always proceeded by extremely slow and continuous adjustments to pressure conditions, and not, as supposed by some geologists,[1] by a series of cataclysmal collapses of the type which would occur if the material of the earth's crust possessed in all circumstances a unique and definite limiting strength analogous to that obtained by crushing a specimen, unsupported laterally, in a testing machine. The further consideration of these problems must, however, be left over for further discussion. Enough has been said to make it evident that the results of Adams and Bancroft have provided much needed data in the light of which many of the existing theories of geodynamics may require considerable modification.

[1] G. A. J. Cole, Presidential address delivered before the geological section of the British Association, Manchester meeting, 1915, *B. A. Report,* pp. 403–20.

APPENDIX

In order to study the experimental data on the flow of rocks in the light of a theory of internal friction, the data reproduced in Tables I and II were obtained from the original large-scale curves obtained by Adams and Bancroft connecting the end load on the steel pistons with the bulge of the nickel-steel jacket. Each of the curves represented the mean of two, three, or more complete sets of observations. The first row of numbers for each specimen is the total load W_0 (in thousand pounds) on the steel pistons required to bulge the nickel-steel jacket by the amounts entered under the various columns. The second row gives the pressure-intensity $P_0 = W_0 \pi b_0^2$ in thousand pounds per square inch exerted on the end of the specimen of radius b_0. The third line gives the average pressure-intensity $P = \widehat{zz}$ in thousand pounds per square inch at the central portion of the specimen in the direction of the axis, correcting for the effect of the bulge from formula (20). It will be noticed that the average longitudinal pressure at the center is somewhat less than that over the ends by amounts which increase considerably with the harder rocks. The final results given in Tables I and II are shown graphically in Plates I and II, respectively. Against the lateral pressures (given by the experiment on tallow) are plotted the longitudinal pressures required to bulge the nickel-steel jacket to the same extent. For such of the rocks as give curves approximating to straight lines we may say that a definite *modulus of plasticity* and *coefficient of internal friction* exist. Rough estimates of these constants as determined for the soft rocks from large-scale curves are given in Table III, in which the first entry corresponds to the 0.25-centimeter wall nickel-steel jacket and the second to the 0.33-centimeter wall. It will be noticed that the two sets of results are in poor agreement for K, and are only in rough agreement for μ, the difficulty arising from attempting to fit a straight line to a series of points which are only approximately colinear.

In the case of the harder rocks no definite coefficient of friction can be said to exist. In the case of dolomite and Belgian black marble it is noticed that the coefficient of friction tends to diminish with increasing longitudinal and lateral stress. Slate gives a very irregular curve due to the development of cracks while the material is stressed. The sudden bend in the curves for diabase and granite is attributed to the actual breakdown of the rock material. From the curves of Plates I and II it will be noticed that this occurs in the neighborhood of $\widehat{zz} = 150{,}000$, $\widehat{xx} = 25{,}000$, corresponding to a stress-difference of 125,000 pounds per square inch. In a general way this result confirms the conclusion already arrived at from a discussion of the experiments of Adams on the pressure required to close up small cylindrical cavities in specimens of Westerly granite. In the writer's paper already mentioned (p. 641, n. 1) it was pointed out that the stress-difference required to break down the rock material in the neighborhood of small cavities amounted to as much as

TABLE I

0.25-Centimeter Wall		1	2	3	4	5	6	7	8	9	10	11	12
Bulge $2b_0=0.7874''$	$2b-2b_0$	0.002 ''	0.004 ''	0.006 ''	0.008 ''	0.010 ''	0.020 ''	0.030 ''	0.040 ''	0.050 ''	0.060 ''	0.080 ''	0.100 ''
	$2b$	.7894''	.7914''	.7934''	.7954''	.7974''	.8074''	.8174''	.8274''	.8374''	.8474''	.8674''	.8874''
	$1-b_0^2/b^2$	0.004	0.010	0.014	0.020	0.023	0.048	0.071	0.095	0.115	0.136	0.176	0.213
Tallow	W_0	6.5	8.2	8.8	9.2	9.6	10.8	11.7	12.5	13.0	13.4	14.1	14.7
	$P_0=\widehat{xx}$	13.4	16.9	18.1	19.0	19.7	22.2	24.0	25.7	26.7	27.5	29.0	30.3
	$\widehat{zz}=\widehat{xx}$	13.4	16.9	18.1	19.0	19.7	22.2	24.0	25.7	26.7	27.5	29.0	30.3
Steatite	W_0	18.0	19.7	20.5	21.3	21.8	24.0	25.6	27.1	28.5	29.8	32.2	34.3
	P_0	36.9	40.4	42.1	43.7	44.7	49.3	52.6	55.6	58.4	61.1	66.1	70.4
	$\widehat{zz}$	36.8	40.2	41.8	43.2	44.1	48.0	50.5	52.8	54.8	56.5	59.6	61.9
Alabaster	W_0	18.0	22.6	24.0	25.0	26.0	29.5	31.9	33.8	35.3	36.6	39.0	41.0
	P_0	37.0	46.4	49.3	51.3	53.4	60.6	65.4	69.3	72.4	75.1	80.1	84.1
	$\widehat{zz}$	36.9	46.1	48.9	50.7	52.6	58.7	62.4	65.2	67.2	68.6	71.1	72.7
Sandstone	W_0	24.5	27.0	27.7	28.7	29.5	32.2	34.5	36.5	38.4	40.0	43.0	45.3
	P_0	50.3	55.4	56.9	58.8	60.5	66.0	70.7	74.8	78.7	82.1	88.2	92.9
	$\widehat{zz}$	50.2	55.0	56.4	58.0	59.5	63.9	67.3	70.2	72.7	74.6	77.8	79.6
Marble	W_0	22.0	26.2	27.5	30.0	31.0	36.2	40.0	43.1	45.2	47.3	51.2	54.7
	P_0	45.1	53.8	56.4	61.6	63.6	74.2	82.0	88.4	92.8	97.0	105.0	112.1
	$\widehat{zz}$	45.0	53.5	55.9	60.8	62.6	71.7	77.8	82.5	85.2	87.5	91.6	94.7
Dolomite	W_0	35.0	38.0	43.0	44.2	45.5	49.2	51.7	53.7	55.4	56.9	59.7	62.5
	P_0	71.8	78.0	88.2	90.8	93.3	101.0	106.0	110.1	113.6	116.6	122.4	128.2
	$\widehat{zz}$	71.6	77.4	87.3	89.3	91.6	97.2	100.1	102.1	103.6	104.5	105.9	107.4
Belgian black marble	W_0	41.0	48.0	49.5	50.6	51.6	54.6	56.8	58.7	60.4	61.9	64.8	67.2
	P_0	84.1	98.4	101.5	103.7	105.8	112.0	116.5	120.4	123.9	127.0	132.9	137.9
	$\widehat{zz}$	83.9	97.6	100.3	101.9	103.7	107.6	109.8	111.5	112.7	113.4	11.46	115.0
Slate	W_0	(53.0)	(56.4)	(56.7)	(56.9)	58.8	62.4	62.8	63.6	64.5	65.4	67.0	69.0
	P_0	(108.7)	(115.7)	(116.3)	(116.7)	120.6	128.0	128.8	130.2	132.3	134.1	137.4	141.5
	$\widehat{zz}$	(108.3)	(114.7)	(114.9)	(114.7)	118.2	122.8	121.1	120.3	120.2	119.5	118.2	117.8
Diabase	W_0	46.0	54.0	58.5	60.7	63.5	68.9	71.5	73.3	74.5	75.5	77.7	79.7
	P_0	94.3	110.8	120.0	124.5	130.2	141.2	146.6	150.3	152.8	154.8	159.3	163.4
	$\widehat{zz}$	94.0	109.9	118.6	122.3	127.5	135.4	137.7	138.5	138.3	137.4	136.3	135.0
Granite	W_0	57.0	69.0	74.0	76.5	77.4	79.0	79.2	79.7	80.5	81.6	84.1	86.6
	P_0	116.9	142.0	151.8	156.9	158.7	159.7	162.4	163.4	165.1	167.3	172.5	177.6
	$\widehat{zz}$	116.6	140.6	149.9	154.0	155.4	153.0	152.4	150.4	149.2	148.2	147.2	146.3
Lead	W_0	7.0	9.1	9.6	10.1	10.4	11.7	12.6	13.3	13.8	14.3	14.9	15.4
	P_0	14.4	18.7	19.7	20.8	21.4	24.0	25.9	27.3	28.3	29.4	30.6	31.9
	$\widehat{zz}$	14.4	18.7	19.7	20.7	21.4	23.9	25.7	27.2	28.1	29.2	30.3	31.4

TABLE II

0.33-Centimeter Wall		1	2	3	4	5	6	7	8	9	10	11	12
Bulge $2b_0=0.7874''$	$2b-2b_0$	0.002″	0.004″	0.006″	0.008″	0.010″	0.020″	0.030″	0.040″	0.050″	0.060″	0.080″	0.100″
	$2b$	.7894″	.7914″	.7934″	.7954″	.7974″	.8074″	.8174″	.8274″	.8374″	.8474″	.8674″	.8874″
	$1-b_0^2/b^2$	0.004	0.010	0.014	0.020	0.023	0.048	0.071	0.095	0.115	0.136	0.176	0.213
Tallow	W_0	10.2	11.4	12.1	12.6	13.0	14.7	16.2	17.3	18.2	18.7	19.8	20.5
	$P_0=\widehat{xx}$	20.9	23.4	24.9	25.9	26.7	30.3	33.3	35.5	37.4	38.4	40.6	42.1
	$\widehat{zz}=\widehat{xx}$	20.9	23.4	24.9	25.9	26.7	30.3	33.3	35.5	37.4	38.4	40.6	42.1
Steatite	W_0	19.0	24.2	25.5	26.5	27.5	30.9	34.0	36.7	39.0	41.0	44.2	46.8
	P_0	39.0	49.6	52.3	54.3	56.4	63.3	69.7	75.2	80.0	84.0	90.7	95.9
	$\widehat{zz}$	38.9	49.3	51.9	53.7	55.6	61.7	67.1	71.5	75.1	77.7	81.8	84.4
Alabaster	W_0	24.0	28.5	30.75	32.3	33.5	37.5	40.7	43.2	45.2	47.0	49.7	52.2
	P_0	49.2	58.4	63.0	66.2	68.7	76.9	83.4	88.6	92.7	96.4	101.9	107.0
	$\widehat{zz}$	49.1	58.0	62.4	65.4	67.6	74.6	79.8	83.6	86.3	88.4	91.0	93.2
Sandstone	W_0	32.5	33.5	35.0	35.7	36.7	40.5	44.1	47.1	50.1	52.5	57.2	61.0
	P_0	66.6	68.7	71.8	73.3	75.2	83.0	90.4	96.6	102.7	10.76	117.3	125.0
	$\widehat{zz}$	66.4	68.2	71.1	72.3	74.0	80.4	86.3	90.8	95.2	98.0	103.7	107.4
Marble	W_0	26.0	31.0	33.7	35.0	37.5	43.5	48.2	51.5	54.5	57.2	62.4	66.7
	P_0	53.3	63.6	69.1	71.8	76.9	89.2	98.8	105.6	111.7	117.3	127.9	136.7
	$\widehat{zz}$	53.2	63.2	68.4	70.9	75.7	86.3	94.1	98.9	103.1	106.5	112.4	116.5
Dolomite	W_0	42.0	47.0	49.5	51.5	53.0	57.8	61.0	63.8	66.1	68.3	72.7	76.5
	P_0	86.1	96.4	101.5	105.6	108.7	118.5	125.0	130.8	135.6	140.0	149.2	156.9
	$\widehat{zz}$	85.9	95.6	100.3	104.0	106.7	114.3	118.4	121.7	124.3	126.0	130.1	132.4
Belgian black marble	W_0	46.5	52.5	54.5	55.7	56.5	60.1	62.9	65.4	67.8	70.0	74.1	77.8
	P_0	95.3	107.6	111.8	114.2	115.9	123.3	129.0	134.1	139.0	143.6	152.0	159.5
	$\widehat{zz}$	95.0	106.7	110.5	112.2	113.7	118.8	122.1	124.8	127.3	129.1	132.3	134.5
Slate	W_0	60.0	69.0	75.0	(75.3)	(75.5)	76.7	79.0	80.2	80.8	81.8	84.7	87.4
	P_0	123.1	141.7	154.0	(155.0)	(255.4)	157.9	162.6	164.8	166.8	168.4	174.4	179.6
	$\widehat{zz}$	122.6	140.4	152.1	(152.4)	(152.1)	151.7	153.3	152.5	152.0	150.5	150.7	150.3
Diabase	W_0	55.0	62.0	69.0	73.0	75.5	82.2	85.0	86.7	88.3	89.9	93.0	96.2
	P_0	114.0	127.4	141.8	150.0	155.1	168.9	175.0	178.2	181.4	184.7	191.1	197.7
	$\widehat{zz}$	113.6	126.3	140.1	147.5	152.0	162.2	164.8	164.7	164.9	164.7	164.6	164.6
Granite	W_0	(60.0)	76.0	80.2	83.2	85.1	89.5	92.0	94.0	96.0	97.8	101.2	104.3
	P_0	(123.1)	156.2	165.2	171.0	174.8	183.9	189.1	193.2	197.3	200.9	207.6	213.8
	$\widehat{zz}$	(122.6)	154.8	163.1	168.1	171.2	176.4	177.9	178.2	178.9	178.6	178.1	177.2
Lead	W_0	10.0	12.0	12.5	13.0	13.7	15.4	16.8	17.8	18.7	19.3	20.0	20.8
	P_0	20.5	24.6	25.7	26.7	28.1	31.6	34.5	36.5	38.4	39.6	41.1	42.7
	$\widehat{zz}$	20.5	24.5	25.6	26.7	28.0	31.5	34.4	36.4	38.3	39.4	41.0	42.7

160,000–200,000 pounds per square inch. The conclusion, there limited to small cavities, is extended by the present experiments of Adams and Bancroft to continuous rock stressed under conditions approaching those existing in

TABLE III

Specimen	K	μ
	(Pounds per square inch)	
Steatite	5,500–1,800	0.24–0.32
Alabaster	4,200–3,100	0.37–0.38
Sandstone	7,500–3,100	0.34–0.40
Marble	850–1,500	0.58–0.52
Lead	850– 500	0.00

the earth's interior, in which circumstances a limiting stress-difference several times greater than that obtained by the usual crushing test must be employed.

NOTE ON THE DEPOSITS CONTAINING HUMAN REMAINS AND ARTIFACTS AT VERO, FLORIDA

E. H. SELLARDS
Geological Survey of Florida, Tallahassee, Florida

The deposits containing human remains and artifacts at Vero, Florida, have been described in the issue of the *Journal of Geology* of January–February, 1917.[1] Among interpretations advanced in connection with that discussion, that proposed by Dr. R. T. Chamberlin differed in one important respect from that offered by the writer. To Dr. Chamberlin it seemed that the fossils found in the stream bed, or most of them, were secondary, having been washed in from a near-by older formation, while the writer held that these fossils were primary. In order, if possible, to harmonize these views, Dr. Chamberlin very considerately returned to Florida for the purpose of re-examining the deposits and was present with the writer at Vero from March 16 to March 20, 1917. Professor E. W. Berry, who is engaged in a study of the fossil plants, was also present, as well as Mr. H. Gunter and Mr. Isaac M. Weills. The additional collections made include potsherds, bone implements, flints, vertebrate and plant fossils.

The banks of both the main and the lateral canals were re-examined, and it was found that the upland formation from which Dr. Chamberlin assumed that the vertebrate fossils had washed was almost if not entirely non-fossiliferous. These new observations have served to define more closely the problems to be solved. It is evident that the fossils found at this locality are primary fossils in the stream bed and were not washed in from the older formation of the uplands near by. It is quite obvious also, both on old and on new evidence, and in conformity with views previously expressed, that the human remains and artifacts of this deposit do not represent burials by human agency as was maintained by Dr. Hrdlička in the former discussion. The stratigraphic evidence on this point is so conclusive that it is certain that the hypothesis of burial by human agency may be eliminated

[1] "Symposium on the Age and Relations of the Fossil Human Remains Found at Vero, Florida," XXV (1917), 1–62.

as a possibility. It thus appears that the problem is confined to a study of the stream fill, and that the determination of the age of the human remains depends upon a correct understanding of the history of accumulation of material within the stream bed.

The view which the writer holds regarding the stream deposit has been expressed in papers previously published. The earliest phase of deposition in this stream bed includes local accumulations of muck which fill holes and channels in the underlying marine shell marl. Another phase which is general and is observed throughout most of the stream valley includes light-colored, often cross-bedded, sands which pass at a higher level into brown or dark-colored sand. This part of the deposit has been designated as stratum No. 2. Above this brown sand is found as a rule an accumulation of alternating layers of sand and muck, stratum No. 3, which when fully developed is capped by a fresh-water marl. The maximum thickness of the stream fill as preserved at the present time is from 4 to 8 feet. The first human bones obtained were in the brown sand beneath the fresh-water marl, and additional bones were subsequently found in this sand. A flint spawl was found in place in the sand and additional flints and two bone implements were obtained from siftings. From the alternating layers of sand and muck which lie above the brown sand human bones and artifacts have been taken in considerable numbers.

As already stated, human bones and implements have been taken from beneath the fresh-water marl. The last bone implement collected on the recent visit to the locality (Florida Survey collection No. 7786) was found beneath this marl and lay at a depth of 4 feet from the surface. The place of this implement is on the south bank 32 feet west of the lateral inlet canal. The bank at this place is relatively high and has retained its capping of fresh-water marl. It is evident, therefore, that the human materials of this deposit were not accumulated by the recent stream. On the contrary, they lie in deposits accumulated at an earlier stage.

The writer's interpretation, as expressed in papers previously published, is that the human remains and artifacts are contemporaneous with the extinct vertebrates of this deposit, and that the age of the formation, according to the accepted interpretation of faunas and floras, is Pleistocene.

THE FOSSIL PLANTS FROM VERO, FLORIDA

EDWARD W. BERRY
Johns Hopkins University, Baltimore, Maryland

The discovery of human remains associated with an extinct mammalian fauna at Vero, Florida, has excited a great deal of local and general interest, and various theories regarding the age of these remains and the manner of their occurrence have already been advanced, and admirable accounts of the local geology have been given by Sellards and others.[1] It is therefore unnecessary for me to repeat any of these details in connection with the present preliminary abstract of my study of the fossil plants.

Plant remains in the form of laminae of impure peat or scattered fruits, chiefly acorns, are present from the bottom to the top of the deposits overlying the shell marl which forms the base of the section. The lower sands (designated No. 2 by Sellards) have yielded no leaves and but few acorns, but the upper bed (Sellards, No. 3) contains many leaf layers alternating with sand laminae, and it is from the latter horizon that all of the plants enumerated in the following pages have been collected, with the exception of one species of acorn which is common to both beds.

Recent and extinct mammalian and other bones occur in both layers, and human remains are also found in both beds. After a thorough study of the local sections and the paleontologic evidence I am convinced that there is no hiatus between beds Nos. 2 and 3 and that there is no great difference in age from the bottom to the top of the section, although it records changing physical conditions and necessarily becomes gradually more and more recent as the top of the section is approached. The lower sand marks the recession of the sea in which the underlying shell marl was formed. The

[1] E. H. Sellards, *Am. Jour. Sci.* (IV), XLII (1916), 1–18; *Eighth Ann. Rept. Florida Geol. Surv.*, 1916, pp. 122–60, Pls. 15–31; *Science*, N.S., XLIV (1916), 615–17; *Jour. Geol.*, XXV (1917), 4–24, Figs. 1–4; R. T. Chamberlin, *ibid.*, XXV (1917), 25–39, Figs. 1–9; T. W. Vaughan, *ibid.*, pp. 40–42; A. Hrdlička, *ibid.*, pp. 43–51, Figs. 1, 2; O. P. Hay, *ibid.*, pp. 52–55; G. G. MacCurdy, *ibid.*, pp. 56–62, Figs. 1–6.

upper beds (No. 3) mark successive seasonal layers of valley filling in the narrow valley of a small stream. This stream was apparently always small, and the marvelous abundance of fossils at this one point seems to be due to a bar or sinkhole or similar cache formed near the junction of the two lateral branches which united near this point to form the main stream. The determinable plants are represented almost exclusively by fruits or seeds, as the leaves, with the exception of the coriaceous oaks, which are abundant, were too thoroughly decayed before they were buried to retain their identity.

The study of such remains is beset with many difficulties. The material has to be sorted without allowing it to dry. It then has to be impregnated with paraffin simultaneous with drying. Finally, identification is hampered by the lack of recent material for comparison, and when the material is identified the determination of the exact range of the still existing species on which so much hinges is a matter of great uncertainty in the present state of our knowledge of plant geography. I am under obligations to, and take this opportunity of thanking, Mr. W. L. McAtee, of the Biological Survey, for determining five species of fruits for me.

The following plant species have been identified from the Vero deposits:

Pinus taeda Linné
Pinus caribaea Morelet
Pinus sp.
Taxodium distichum (Linné) Rich.
Carex sp.
Pistia spathulata Michx.
Seronoa serrulata (Michx.) Hooker
Sabal palmetto (Walt.) R. & S.
Myrica cerifera Linné
Leitneria floridana Chapman (?)
Quercus virginiana Mill.
Quercus Laurifolia Michx.
Quercus Chapmani Sargent (?)
Quercus brevifolia (Lam.) Sargent
Polygonum sp.
Magnolia virginiana Linné
Anona glabra Linné
Brasenia purpurea (Michx.) Caspary
Ilex glabra (Linné) A. Gray
Acer rubrum Linné
Zizyphus sp. (new species)
Vitis cf. rotundifolia Michx.
Vitis sp.
Benzoin cf. melissaefolium (Walt.) Nees
Viburnum nudum Linné
Viburnum cf. dentatum Linné
Xanthium sp.

The most abundant form in the preceding list is *Quercus laurifolia*, which is represented in the upper beds by leaves, cupules, and acorns and in the lower beds by cupules and acorns. It is still

found growing in the Vero region, but is not nearly so abundant as far south as Vero at the present time as it appears to have been at the time the Vero deposits were laid down.

SUMMARY

The foregoing comprise more or less positively identified remains of twenty-seven species of plants. Nineteen of these have not been previously found fossil, while the following eight have already been discovered in Pliocene or Pleistocene deposits:

Pinus taeda	Brasenia purpurea
Taxodium distichum	Acer rubrum
Quercus virginiana	Zizyphus sp.
Magnolia virginiana	Viburnum nudum

The problem in so far as it relates to the evidence of the plants depends on the correct evaluation of the change which this plant assemblage shows when compared with the flora now growing at Vero.

Of the plants found fossil the following are still found at Vero, and I have included in this list as probably found in the present flora of Vero the four forms of *Pinus*, *Carex*, *Polygonum*, and *Xanthium* which are not specifically identified. This list comprises:

Pinus caribaea	Quercus brevifolia
Pinus sp.	Polygonum sp.
Carex sp.	Magnolia virginiana
Serenoa serrulata	Ilex glabra
Sabal palmetto	Acer rubrum
Myrica cerifera	Vitis cf. rotundifolia
Quercus virginiana	Xanthium sp.
Quercus laurifolia	

In addition to the foregoing fifteen species still found at Vero the following two species are found growing within ten or twelve miles of Vero:

Taxodium distichum	Anona glabra

Three species approach to within about fifty miles of Vero, being recorded from the southern extension of the lake region flora of the central peninsula in De Soto County. These are:

Pinus taeda	Viburnum nudum
Pistia spathulata	

The following six species are not now found growing in peninsular Florida:

Leitneria floridana (?)	Vitis sp.
Quercus chapmani (?)	Benzoin cf. melissaefolium
Brasenia purpurea	Viburnum cf. dentatum

Of these *Leitneria floridana* is a very local form not found nearer than the Apalachicola River, and the chief center of growth of *Quercus chapmani* is also in west Florida, while the true *Viburnum dentatum* does not occur nearer than the upland region of Georgia.

Finally, the Vero deposits have yielded a fruit probably identical with similar remains from the late Pleistocene of New Jersey representing an entirely extinct species of *Zizyphus*, a genus abundant in Southeastern North America during the Tertiary, but not now represented except by a single species of the arid southwest (Texas to Arizona).

Two of the fossil species have been recorded from the Pliocene. These are *Taxodium distichum* and *Magnolia virginiana*. One, *Quercus virginiana*, is found in the early Pleistocene of both Kentucky and Alabama, and the following occur in the late Pleistocene:

Pinus taeda	Acer rubrum
Taxodium distichum	Zizyphus sp.
Quercus virginiana	Viburnum nudum
Brasenia purpurea	

These latter, while they constitute but 26 per cent of the known fossil flora at Vero, are especially significant in connection with the fact that they all occur elsewhere in the physiographically youngest of the Pleistocene terrace deposits, namely, the Talbot of New Jersey and Maryland, the Chowan of North Carolina, and the corresponding lowest terrace at several localities in Alabama, while the Vero deposits constitute the youngest physiographic terrace plain of the region and are referred to the Pensacola terrace by Matson.[1]

In my judgment and in the ordinary acceptance of that term this flora is unquestionably of late Pleistocene age.

[1] G. C. Matson, *U.S. Geol. Surv., Water Supply Paper 319*, 1913, pp. 31–35.

Regarding its bearing on the interesting problem of the age of the human and associated mammalian and other remains at Vero, my study of the locality furnishes the following somewhat categorical conclusions. The underlying shell marl which forms a definite and undisputed datum plane is late Pleistocene in age. Its species all exist in near-by waters at the present time, and many of them have been recorded from shell marls found from southern New Jersey to the Florida keys and forming a part of the lowest and latest well-defined terrace plain previously mentioned as having been named Talbot in Maryland, Chowan in North Carolina, and Pensacola in Florida. It follows that the vertebrate remains which are so numerous at Vero cannot possibly be of Middle or early Pleistocene age unless they are regarded as having been reworked from older deposits, and I cannot conceive that this was possible, nor do the vertebrate paleontologists who have examined the deposits consider that such was the case. In fact, I believe that, if it had not been for the overestimate of the age of this vertebrate fauna, Dr. Chamberlin would not have advanced his hypothesis of the reworking and mechanical mixing of these bones and Dr. Hrdlička would not have insisted on the human burial theory to account for the presence of the human skeletal remains. Nothing is more reasonable than to suppose that the larger elements in the Middle Pleistocene fauna of more northern areas should have lingered for thousands of years in this more genial southern clime until the presence of man in considerable numbers and the changing climate as is attested by the fossil plants should have brought about the extinction of a large percentage of the fauna. The fauna itself confirms the rather limited data furnished by the fossil flora of this change in climate, since it indicates a more mesophytic habitat than exists today in the vicinity of Vero. Regarding the burial theory of Dr. Hrdlička it may be said that a part of the plant material came from immediately above one of the human skeletons, and I cannot conceive of the possibility of not being able to see evidence of artificial burial in material made up of alternate layers of sand and matted leaves and other vegetable débris. I therefore see no reason to doubt that relative modern men were contemporaneous with this partially extinct fauna of Middle Pleistocene

aspect which survived in Florida to the late Pleistocene. With regard to the exact age of the Vero deposits there are, it seems to me, but two alternatives, and these apply equally and are in large part derived from a study of the physiography and the faunas and floras of the corresponding topographic forms in the other states of the Coastal Plain. These alternatives are that they are about the same age as the Peorian interglacial deposits of the Mississippi Valley or are immediately post-Wisconsin and correspond with what the Scandinavian geologists have named Litorina time.

FURTHER STUDIES AT VERO, FLORIDA

ROLLIN T. CHAMBERLIN
University of Chicago

In a recent number of this *Journal* there appeared a symposium on the age and relations of fossil human remains found near Vero, Florida.[1] The several investigators attacked the problem from quite different viewpoints and developed considerable difference of opinion. Later Dr. Sellards planned to spend an additional week at Vero with Dr. E. W. Berry in further study of the critical points involved in the case. He was good enough to invite the writer to join in this further inquiry, and this invitation was cordially accepted. As a result of the wider examination of essential points made possible by my second visit, I desire to amend and extend the interpretation of the history of the human bones and associated relics previously offered.

My studies on the first visit were given almost wholly to an endeavor to work out the physical history and time relations of the formations at Vero, as this was regarded as a step necessary to the safe interpretation of the relics embraced in them. This seemed especially necessary because the dates of the appearance of man and of the disappearance of the extinct animals were among the very points brought into question and could not themselves be used as decisive criteria. On the other hand, the nature and successions of the formations afford some of the most critical evidence bearing on these dates. It will perhaps be recalled that the history of the formations was found to be rather definitely deployed, and that the time relations of the deposits were quite well indicated by the physical criteria available, irrespective of their fossil contents. My former reading of this history was confirmed in all essential

[1] E. H. Sellards, R. T. Chamberlin, T. W. Vaughan, Aleš Hrdlička, O. P. Hay, and G. G. MacCurdy, "Symposium on the Age and Relations of the Fossil Human Remains Found at Vero, Florida," *Jour. Geol.*, XXV (1917), 1–62.

particulars by what was seen during the second visit. Its essentials are here recalled for the sake of the discussion following.

1. During a submergence of this portion of the east coast of Florida there was laid down a striking marine shell marl which has sometimes been called "coquina." It is the oldest formation exposed to view and has been referred without question to the Pleistocene. Though its precise place within the Pleistocene has not been determined, its fauna was essentially the same as that now living in the adjacent ocean. Following the deposition of the marine shell marl, a withdrawal of the sea gradually brought this region into the horizon of terrestrial action. In the transition, beach conditions prevailed, resulting in sandy deposits, partly marine, partly terrestrial.

2. At the appropriate stage in the withdrawal of the sea a barrier ridge was developed immediately to the west of the present location of the Florida East Coast Railway. This ridge parallels the railroad and the coast for many miles both north and south of Vero, and throughout most of its extent it is a pronounced topographic feature. West of it was a marshy area.

3. With further withdrawal of the sea a newer barrier ridge developed from two to two and one-half miles east of the earlier Vero beach ridge. This constitutes the present east coast of Florida. For over one hundred miles it incloses, between itself and the mainland, a salt-water lagoon, known as the Indian River.

4. After the withdrawal of the sea from the Vero beach ridge, erosion developed a channel in essentially the position now occupied by Van Valkenburg's Creek. The very low gradient and notable width of this channel in proportion to its very insignificant depth, which was limited by sea-level, suggest that erosion, which here was slow at the best, was in progress for a considerable time.

5. In the marshy region west of the Vero beach ridge bog deposits accumulated here and there. Cementation had also affected certain horizons of the sands of this tract and had converted them into a sandstone. This had been effected by the deposition of iron and manganese oxides as well as organic matter in the sands. The length of time involved in this process of conver-

sion of the sands into sandstone may well have been considerable, though it cannot be definitely measured.

6. But, whatever the length of this period, it is important to observe that *the filling of the channel of the creek* did not begin until *after the sand had been converted into black sandstone*, for water-worn pebbles of this black sandstone *are abundant in the basal portion of*

FIG. 1.—The present channel of Van Valkenburg's Creek, dry since the construction of the drainage canal in 1913. Shows the relatively slight depth of the channel.

the channel fill. They are in fact rather more conspicuous at the base of the fill than at higher levels, although occurring throughout. The special significance of these black pebbles, as brought out in the symposium, lies in the fact that they fix the date of the filling of the channel with respect to the old bog area to the west. The oldest fill in the creek channel is notably younger than the bog deposits of the uplands back of the main beach ridge.

7. The filling of the creek channel from this beginning up to the present has taken place in two stages, which appear to be quite

distinct in some portions of the channel, but which at some other points can be separated only with much doubt. At best they are thin, both of them together averaging only 5–7 feet in thickness, and they are quite changeable in composition. The lower of these has been designated formation No. 2 by Sellards and the upper one formation No. 3. In this paper the former will be termed the lower creek deposit and the latter the upper creek deposit. The bones and relics in question were found in these two creek deposits.

The discrimination of these successive stages of formation made it seem quite possible that the land life of the times began to occupy this region during the stages of emergence, and hence that bones of the extinct mammals and other vertebrates might have accumulated in the marshy area to the west of the Vero beach ridge in Pleistocene times, following not long after the coquina stage, and that later, as Van Valkenburg's Creek gradually cut back into this area, these old Pleistocene bones were washed into the stream channel and concentrated in the creek deposit, while at this later time there mingled with them relics of the more recent vertebrates and plants, as well as human remains.[1] Thus the deposit of the stream channel might contain fossils of quite different ages in intimate association. The geologic conditions and the sequence of events seemed such as to suggest and to support this hypothesis.

On the assumption that the extinct mammals were perhaps as old as Middle Pleistocene—as was then urged—and that the coquina formation which underlies the region could not well be interpreted as much older than this—if indeed as old, since all of its fossils belong to living species—there seemed to be rather urgent reasons for presuming that at least the older of the extinct mammals invaded the region as soon after its emergence from the sea as conditions permitted. They were therefore supposed to have been present during the formation of the marsh deposit back of the beach ridge, and to have, in all probability, been buried in it, and their relics derived from it in the subsequent trenching and filling by Van Valkenburg's Creek. The finding of balls of black sandstone from the marsh deposit in both the older and the younger creek deposits seemed to fit at once, and help explain, this very

[1] Symposium, pp. 25–39.

puzzling combination of bones of extinct animals of supposedly Middle Pleistocene age mingled with fragments of human pottery of almost obvious recency.

The actual presence of bones of the extinct animals in this Pleistocene marshy area was not observed, for, on the first visit, time did not permit an adequate examination. And so a leading

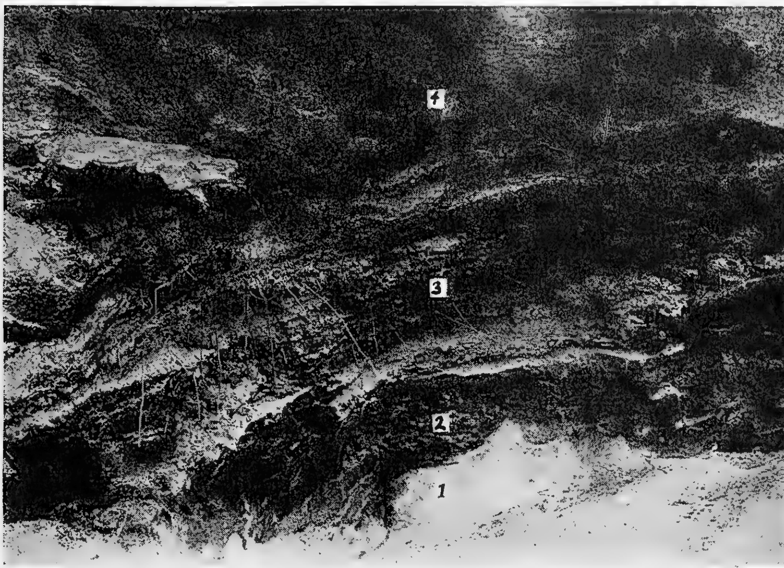


FIG. 2.—The formations of the creek section exposed by digging into the south bank of the canal near point marked *N* in Fig. 4. No. 1 represents the marine shell marl (coquina) grading upward into light-colored sands; No. 2 is the lower creek filling of variously stained sands (Sellards' formation No. 2); No. 3 represents the upper creek filling (Sellards' formation No. 3), consisting of alternate layers and lenses of sand and muck; No. 4 is the loose dump material piled on the surface in excavating the canal.

purpose of the second visit was to search the older upland formations for direct fossil evidence on this point. This search was not successful in finding bones of the extinct animals, either *in situ*, or in the canal dump from the upland area through which the two forks of the creek have cut. The conditions that prevailed at the time of the marsh deposit to the west of the barrier ridge seem to have been inhospitable to life of the types of the extinct animals

in question, or else the nature of the formation was unfavorable to their preservation. This, of course, is not conclusive evidence that they did not then live in the region, but it greatly weakens the hypothesis that bones deposited in these beds were sources of supply to the creek deposit after the analogy of the black pebbles.

Bones as well as coarser fragments of any durable material should, of course, tend to become concentrated in a stream bed as the finer inclosing sands are washed downstream. This is a well-recognized principle and it might well account for the fact that bone fragments are rare in the upland formations and numerous in the creek channel deposits. But whether this selective concentration of coarser fragments in the channel by the action of the stream is quantitatively adequate to explain the difference is questionable, and it is not wise to appeal to it unless all other explanations fail. The solution of the riddle of the mixture of the bones of extinct animals with human bones and pottery was therefore sought on other lines.

It is true that, at a point three miles west of Vero, Dr. Sellards had found the wreck of a proboscidian in a fresh-water marl deposit close to the surface and referable to the general upland deposit back of the beach ridge.[1] Dr. Sellards had also recognized a fauna similar to that found in his formation No. 2—the lower creek deposit—in a fresh-water marl bed belonging to the upland deposit at a point about 1,700 feet east of the Florida East Coast Railway bridge, i.e., *downstream* from the deposits which contain human relics. Both these facts seem to imply that a fauna of the general type found in the lower creek deposit occupied the region at some time during the formation of the upland deposits, and to this extent they support the general correctness of the inferences entertained in my contribution to the symposium, but they do not support the specific view that the bones of the lower creek deposit were in any large measure derived from the lagoon, or marsh, deposit of which the indurated black sand is a part.

These facts also weaken the presumption that the relics of the extinct animals really imply so great age as Middle Pleistocene. Dr. Hay, who favored the view that they were closely related to

[1] Symposium, p. 55.

the fauna of the Aftonian inter-glacial beds of Iowa, yet recognized that "this fauna might have continued on for another stage or two, but by the time of the Illinoian drift it had become essentially modified."[1] It is further to be recognized as not improbable that this fauna may have lingered longer at the south than it did at the north, where the advances and retreats of the ice border were putting the fauna under the stress of an oscillating climate.

The marine coquina deposit, which lies below all the upland beds and the creek deposits as well, does not bear evidence of great age, its shells being all of living species. This deposit, or perhaps more strictly the beach sands into which it grades upward, are referred by the geologists of this and adjoining states to what has been termed the third or lowest Pleistocene marine terrace formation. The age of this terrace was assigned by Matson to late Pleistocene.[2]

There are good reasons, therefore, in the stratigraphy and the topographical aspects of the deposits at Vero, for regarding the extinct mammals and other vertebrates as continuing to a relatively late date. The aspects of the problem thus developed made a closer scrutiny of the two creek deposits more imperative, for, as we have seen, both of these deposits were late in the history of the formations of the region, and the oldest of these formations bears both a paleontological and a topographical aspect of relative recency.

This closer scrutiny at the time of the second visit developed evidence both for and against the point previously made by Dr. Sellards that the delicate condition of the fossils—as well as their grouping—was not consistent with the view that they were derived from an older formation by stream action. Dr. Sellards put forward an increasing number of fossil remains which, on account of their fragile nature, or because of the close association of various bones, he did not believe could have suffered transportation or much disturbance since fossilization. That an occasional specimen of this sort need not be of much significance was pretty effectually established by the finding, among a half-dozen fragile

[1] Symposium, pp. 54–55.

[2] *Ibid.*, p. 40; G. E. Matson, "Geology and Ground Waters of Florida," *U.S. Geol. Surv., Water Supply Paper 319*, 1913, pp. 31–35.

carapaces of turtles, of one specimen still firmly holding together and undoubtedly still capable of being swept along by a stream for a considerable distance without being torn to pieces. But the cumulative evidence of the cases presented suggested strongly that various particular individuals, at least, were primary fossils but little disturbed since entombment.

On the whole, it seems to me that Dr. Sellards has strengthened his view that at least an essential part of the fossils of the lower creek deposit are primary to that deposit, and that the extinct animals represented by these fossils were denizens of the region as late as the formation of the lower creek deposit, Sellards' formation No. 2. This does not entirely dispose of the hypothesis that some of them were washed in from the older deposits in the process of stream-cutting and stream-filling, but it renders that possibility less vital to the essential question—the time of man's appearance in this region. At the same time, of course, it brings the time of extinction of the fauna of the lower creek deposit down to a relatively recent date.

It, however, left the critical feature of the problem—the admixture of extinct animals with human remains, pottery, and bone implements of modern aspect—still crying for a satisfactory explanation. The crux of the whole problem seemed to be thrown upon the trustworthiness of the discrimination between the upper and the lower creek deposits. Now these upper and lower deposits altogether measure only about 6 feet in thickness on the average. This is a pretty thin deposit to divide into two distinct ages when the natural irregularity of such deposits is considered, and when the composition of the earlier and the later deposits is so nearly the same as it is in this case. The upper creek deposition reaches down to the year 1913, when the digging of the drainage canal put an end to the activity of this portion of Van Valkenburg's Creek, and thus the occurrence within it of pottery, bone implements, and the remains of man is altogether what one might expect. But the presence of these same relics in the lower creek deposit would tell a different story. It therefore becomes imperative to note sharply in just what portions of the creek filling the significant relics were found. It is also equally important to determine critically in what

horizons within the creek deposits the undisturbed individuals of the extinct vertebrates occur. Creek deposits, by their very nature, imply changing conditions from time to time.

Dr. Sellards had appealed to, as evidence against the secondary nature of the fossils of the old vertebrates, a number of bone assemblages, such as a tapir skull, a wolf's head, an armadillo,

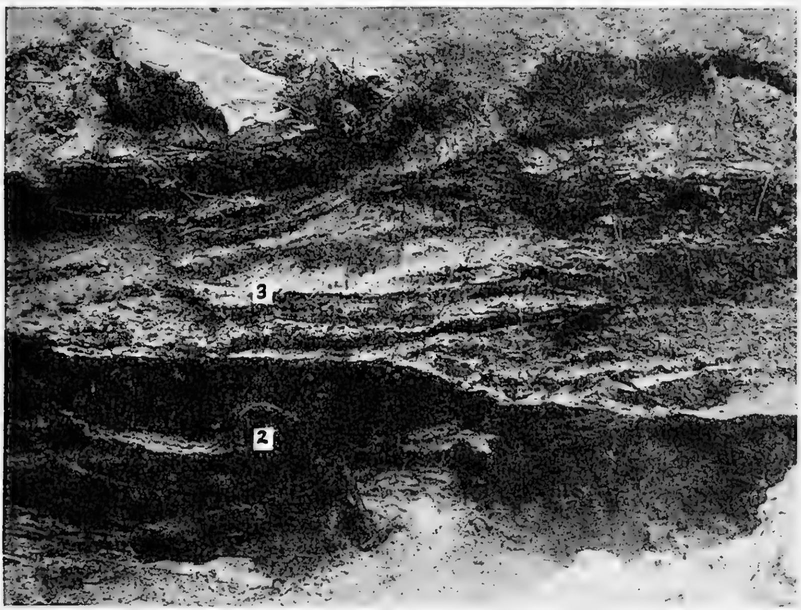


FIG. 3.—View showing a distinct dividing line between the lower creek filling (No. 2) and the upper creek filling (No. 3). Lenses and irregular patches of material in both formations rapidly pinch out, showing considerable scour and fill. Location close to that of Fig. 2, but at a different stage in the progress of the exploratory digging in March, 1917. At the base is the underlying formation No. 1; at the top is the canal dump piled on the surface. Note the thinness of the creek fillings.

turtle carapaces, etc., which he did not believe could have been moved since fossilization. In going over the list one by one with Dr. Sellards, it developed that the fossils of old extinct forms which seemed to him to necessitate the belief that they have not been rewashed, were found in formation No. 2 (the lower creek deposit) and in general rather well down in it. Here must perhaps be

excepted the turtles, but the finding of one very firm carapace near the junction of the two deposits would seem to throw much doubt upon arguments based upon the turtles. If it be admitted, then, that such of these fossils as cannot readily have been transported from elsewhere since fossilization are primary to the lower creek deposit, that would mean that this earlier creek filling is of the same age as these particular types, and so its age is determinable from these types provided they afford decisive evidence. But a development of scarcely less significance in the ultimate interpretation was the bringing out of this very fact that the undisturbed specimens of extinct vertebrates were taken wholly, or chiefly, from the lower creek deposit.

On the other hand, according to the published accounts of Dr. Sellards, the bones of the extinct vertebrates found in the upper creek deposit are much scattered, commonly a few teeth, or a lower jaw, or fragments of one or two other bones.[1] In this condition they do not seem to the writer to preclude more or less reworking by the creek, but rather to imply it.

Next let us consider the location of the human bones and artifacts. On the north bank of the canal the human relics thus far found have come exclusively from the upper creek deposit. No evidence of the presence of man has yet been discovered in the lower creek deposit on the north bank of the canal. At the same time it strikes the writer as an observation equally to be emphasized that the two creek deposits are quite distinct from one another throughout this section along the north bank of the canal. In this section the observer feels little hesitation in drawing the dividing line, and different investigators readily place it at the same level. It can scarcely be without significance that the human relics found thus far in the north bank of the canal all lie *above* this well-marked dividing line, while the vertebrates of greatest age, and those which present the best basis for the claim that they cannot have been rewashed, lie *below* this line.

All the human relics reported to have come from the *lower* creek filling were found in the *south* bank of the canal, and were

[1] E. H. Sellards, "Human Remains and Associated Fossils from the Pleistocene of Florida," *Eighth Ann. Rept. Florida Geol. Surv.*, 1916, pp. 147–52.

obtained from points marked *M* and *N* on the contour map (Fig. 4). It was at point *M* that the original discovery of human bones was made by Mr. Frank Ayers in October, 1915. But since that time the bank at this point has been cut back five or six feet in further search for bones, so that the exact resting-place of this first find of bones can no longer be viewed. According to the description given by Dr. Sellards, these human remains, or skeleton No. 1 as it

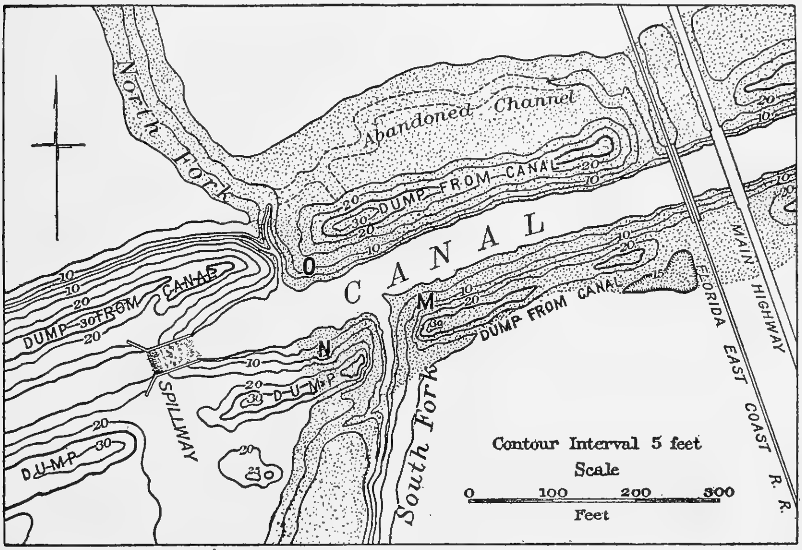


FIG. 4.—Detailed map of the locality where the human bones were found. The canal and the resulting dump piles have done much to change the original topography. The dotted area represents the flood-plain of Van Valkenburg's Creek as it appears to have been just prior to the digging of the canal. The first human skeleton was found at point marked *M*, the second at point marked *N*, while human relics were found also at point *O*. (Reproduced from Symposium, p. 26.)

may be called, were imbedded in brown sand about two feet from the surface of the ground as it existed previous to the construction of the canal.[1] Of these two feet, nine inches, next above the bones, consisted of brown sand, above which lay one foot three inches of sandy, fresh-water marl. All of this was originally assigned to the lower creek fill. If this be correct the upper filling is wanting at

[1] *Op. cit.*, pp. 131–32.

this place. But in his symposium paper Dr. Sellards had come to regard this marl as probably equivalent to formation No. 3 (upper creek fill),[1] and in that article assigned to it a thickness of 18 inches.[2] Only a few inches of brown sand therefore remain as a basis for referring the bones to the lower creek deposit in a case in which the correct reference is a matter of critical importance. The case accordingly does not seem to the present writer to be one that may safely be regarded as conclusive.

The other human remains reported from the lower creek deposit were obtained in the extensive diggings carried on at the point marked *N* in Fig. 4. In the section at this point the lower fill shows extreme irregularity. This is assigned to subsequent scour and fill, evidences of which are more marked here than anywhere else in the sections exposed by the canal excavations. Cutting by the stream has been so pronounced that, in the midst of the area over which the bones are scattered, the lower deposit has at one point been completely removed, and the upper filling rests in a depression cut into formation No. 1 (the underlying marine beds).[3]

A few feet to the west of this more human bones were found along the contact line of formations Nos. 2 and 3 (the upper and lower creek deposits), or slightly within the basal portion of the upper creek deposit. Because of the close association of these two finds, because there is no duplication of parts, and because all the bones came from a large individual, Dr. Sellards believes that the bones mentioned in the last paragraph and referred to the lower fill and those here mentioned as found a few feet to the west along the contact of the two fillings, all belong to the same skeleton.[4] This may be called skeleton No. 2.

If these bones all belong to one skeleton, the fact that a part of them were found in formation No. 2, as interpreted by Dr. Sellards, and a part of them in the base of formation No. 3 requires explanation. This naturally led to the suggestion that those bones which were found in the basal portion of the upper fill reached that position by being washed out of the lower deposit.[5] If, however, one examines Fig. 6 of the Florida state report, it is seen that the bones

[1] Symposium, p. 17.

[2] *Ibid.*, p. 22.

[3] *Eighth Ann. Rept.*, etc., Fig. 6, p. 137.

[4] *Ibid.*, p. 142.

[5] Symposium, p. 54.

found in the basal portion of the upper deposit are *upstream* from the point where the bones in the lower deposit occur. Besides this, two out of the three bones are figured as occurring at a considerably higher level than the bones in the lower deposit. At the same time the attitude and appearance of these suggest that they had already moved somewhat down the rather steep slope implied by the depositional lines.

These suggestive relations occur at the most critical locality. It was here that most of the collecting was done, not only during this later visit, but also during the previous one. From the geological point of view this section is peculiar in that here there has been more obvious scour and fill by the stream than elsewhere. This is made evident by an unusual number of pockets and lenses of sand and muck, as well as rapid dovetailings of layers. It may be worthy of note also that the section here lies beneath the latest channel of Van Valkenburg's Creek. The pockets, "filled holes," lenses, and dovetailings render the identification of the true line between the lower and upper creek deposits both difficult and uncertain. While the line of division is reasonably distinct at most points elsewhere, as on the north bank already noted, it unfortunately becomes obscure in this critical section.

In the course of our examinations there frequently arose questions as to the line of division between the upper and lower deposits, and sooner or later the judgments of all members of the party were more or less involved in these efforts at discrimination. These questions revealed the fact that there were notable differences of opinion as to whether a given bit of a section belonged to the upper or lower deposit. If, as discussion and critical consideration proceeded, there was noticeable a tendency to shift the dividing line in one direction rather than another, it was to give the base of the upper creek filling a lower place in holes and hollows than it had been assigned before. In other words, there was a general disposition, as the result of progressive study, to lower the division line. This justifies the inference that any sharp division of the creek deposits in this portion of the south bank into distinct formations is lacking in complete conclusiveness.

A specific case of this kind of uncertainty is illustrated by Fig. 5. As a result of much digging for fossils at this point, the bank had gradually been cut back till, at the taking of this picture, it was perhaps 15 feet back from its original canal face. The entire thickness of the deposit from the base of the black muck and sand fill

FIG. 5.—Section of south bank of the canal near point marked *N* (Fig. 4) as exposed by the party on March 21, 1917. At the base are buff marine sands with some shells (formation No. 1); No. 2 above is the lower creek fill which was originally supposed to extend up to the prominent line of white sand lenses, just beneath marker 3 in the middle of the picture; but upon more critical inspection, the patches of fill marked 3*a* and 3*b* were excluded from the lower fill and placed in the upper fill. No. 3 represents the unmistakable upper creek fill. It contains some small lenses and pockets of marine shells derived from formation No. 1.

(just to the left of the hammer) to the surface as it was in 1913, just prior to the excavation of the canal, is $5\frac{1}{2}$ feet. As the party viewed the newly exposed section for the first time, all were ready to carry the upper creek filling down to the prominent line of whitish sands and reworked coquina shells just beneath marker 3 in Fig. 5. After a brief inspection, there seemed to be reasons for assigning the block

marked 3*a* (Fig. 5) to the upper creek deposit. And then the upper deposit was extended downward to include the peculiar funnel-like fill marked 3*b*, while the writer, at least, would hesitate to deny that the upper deposit might not, in reality, include also some of the material which reposes in lenslike fashion adjacent to this funnel. In any case it is clear that there was much scouring and filling at this point, and this involved the lower as well as the upper deposit. This suggests that the scour and fill arose from the course of the stream at this point—some turn, perhaps, or some configuration of its channel.

The peculiar funnel-like filling marked 3*b* was so obvious as to suggest the name "funnel," as it was evidently a deep hole in the creek bed filled with alluvium. After the photographs were taken, further excavations were made, and at the bottom of the funnel the carapaces of two turtles were found. One of these, still firm and strong, has already been referred to (p. 676). With further horizontal digging into the bank the funnel quickly disappeared.

This particular locality has been a gold mine for bone-collecting, and far more excavating has been done here than at any other point. The writer suspects that one reason why this particular area has proved so prolific in results is that there was an exceptional reworking of material by the stream at this point, resulting in a greater concentration of bones, pottery, and coarser material. At the same time, this material was left in more unusual positions than in places where the stream action has been simpler. In fact, small lenses and stringers of shells derived from the erosion of the underlying marine coquina are frequently seen here, not only in the lower creek deposit, but in the upper creek deposit as well. If, then, the upper creek deposit has received an appreciable portion of its material from the more deeply buried marine beds, how much more of its material must have been derived from the far more accessible lower creek deposits which overlie these marine beds. The mixing of materials is obvious.

In view of the similarity of the upper and lower creek deposits, and the inevitable difficulty of drawing a perfect line of division between them; in view of the actual differences of opinion as to

just where such line should be drawn, and of changes of opinion once formed; in view of the natural doubt as to whether two such deposits measuring together only about six feet could in fact remain altogether unmixed and distinct; and in view of the observed fact that the stream, in its later action, actually did cut entirely through its own earlier deposits and into the marine formation below, it would seem that grave doubts as to the trustworthiness of correlations of this stream material may well be entertained. Perhaps it is obligatory that they should be entertained. The balance of evidence seems to lie in favor of including all doubtful horizons in the upper fill, since the upper fill does penetrate deep into the lower fill at so many points. The human bones and relics would seem to the present writer to belong to the upper creek deposit, which was contemporaneous with the human occupation of Florida. This interpretation would allow the correctness of Dr. Sellards' contention that the bones of the extinct vertebrates well down in the undisturbed part of the lower creek deposit are fossils primary to that deposit. With this revision of the stratigraphic view, the testimony of the inherent character of the human relics rises into scarcely less than decisive importance.

Now, among the human relics, the pottery seems to carry the most telling testimony as to the time when the aborigines dwelt on the banks of Van Valkenburg's Creek. The association of the pottery with the human bones may well be regarded as peculiarly significant, for the pottery was a human product and it carries a time relation. Fragments of pottery, in more or less abundance, were found on the second visit at as low a horizon in the creek deposits as were any of the human bones. The writer saw no evidence of any human race earlier than the pottery-makers, and no such earlier race has been claimed. Now, as MacCurdy,[1] Hrdlička,[2] and Holmes[3] have pointed out, the pottery belongs to the type which was used by the mound-building Indian tribes of Florida. Such pottery was in common use in the middle or later Neolithic age. This pottery, of itself, would not therefore be assigned a date earlier than mid-Recent. Even in Europe, where the presence and

[1] Symposium, pp. 60–62.

[2] *Ibid.*, pp. 47–50.

[3] *Ibid.*, p. 51.

development of man has been traced from the mid-Pleistocene on, the introduction of pottery by Neolithic man is not placed as far back as the close of the Glacial period and is not, therefore, Pleistocene as usually defined. There is no ground to suppose that pottery was in use in North America before it was in use in the Old World; more probably it was introduced here later.

If (1) the testimony of the human relics, particularly that of the pottery, be taken at its apparent paleontological value; if (2) the upper creek fill, whose accumulations demonstrably continued on until 1913, be regarded as embracing all the human relics, as seems quite consistent with the physical evidence; if (3) the critical extinct vertebrate fossils found in this upper creek fill be regarded as derivatives from the lower creek fill; and if (4) the lower creek fill be regarded as contemporaneous with the last living stages of the extinct vertebrates whose fossils it holds as primary inclusions, as Dr. Sellards contends, the whole history becomes consistent physically and paleontologically, and the gist of its lesson is that the Pleistocene fauna lived longer in this genial southern clime than it has been credited with in the more northern latitudes, while the evidence of man's presence here falls into harmony with the general tenor of other evidences which fail to assign him an antiquity beyond the mid-Recent.

ANOTHER LOCALITY OF EOCENE GLACIATION IN SOUTHERN COLORADO[1]

WALLACE W. ATWOOD
Harvard University, Cambridge, Massachusetts

Since the publication of the paper on the Eocene glaciation recorded at the northwest base of the San Juan Mountains near the village of Ridgway,[2] the author's attention has been called to a similar discovery made by Mr. Charles W. Drysdale in British Columbia at about the same time.[3]

When Eocene till was found near Ridgway, and the formation was given the name Ridgway till, it was anticipated that other glacial deposits of the same age would soon be recognized in other parts of the Rocky Mountain province. Each of the larger ranges in this great geographic province has had a history somewhat similar to that of the San Juan Mountains. These ranges were all uplifted, some as great anticlinal arches, some as domes, and others with some faulting and intrusion, at the close of the Mesozoic era or beginning of the Cenozoic time. Those great arches and domes were dissected into mountain forms, and, when favorable climatic conditions prevailed, glaciers probably formed in many of the higher basins among those mountains and assisted in the further dissection of the ranges. Now that Eocene till has been discovered in British Columbia, and at a locality to be herein described near the south margin of the San Juan Mountains, it appears to be well established that conditions favorable for the formation of Alpine glaciers did obtain in the western portion of North America during early Tertiary time.

[1] Published with the permission of the Director of the United States Geological Survey.

[2] W. W. Atwood, "Eocene Glacial Deposits in Southwestern Colorado," *U.S. Geol. Survey, Prof. Paper 95-B*, 1915.

[3] C. W. Drysdale, "Geology of Franklin Mining Camp, British Columbia," *Canadian Geol. Survey Mem. 56*, 1915.

The locality at which this most recent discovery of Eocene till in Colorado was made is about 20 miles southeast from Pagosa Springs and in the south-central portion of the Summitville quadrangle of the United States topographic atlas.

The deposit is exposed in the valley walls of White Creek where that stream is dissecting the surface of V Mountain. The best exposures may be reached by trail from the Blanco Basin, following the base of the bold mountain escarpment just east of V Mountain to a large lake held in by recent landslides, and thence westward half a mile to the junction of the two upper forks of White Creek.

The ridge between the two upper forks of White Creek and that west of the west fork are composed of this ancient till, but on their surfaces there are fragments of the later Tertiary volcanics that have fallen or been washed from the mountains to the east.

The till is composed of stones ranging up to 5 feet in diameter imbedded in a clay matrix. Many of the stones are distinctly striated, and most of them are subangular and beautifully polished and planated. The notable character of this till, however, is the abundance of stones that have come from the pre-Cambrian formations, now nowhere exposed near this locality, and the many bowlders known to have come from the Cutler or Dolores formations of Permo-Triassic age which must also be buried in the core of the range. Of equal significance is the absence of stones from the later Tertiary volcanics. These two points make it clear that the ice which deposited this till formed and accomplished its work during the time when the pre-Cambrian core of the range and the upturned Paleozoic and Mesozoic formations were exposed at the surface, and before the later Tertiary lavas and tuffs were present.

The stones in this till consist of granites, quartz, quartzites, schists, gneisses, jaspers, red sandstones from the Cutler or Dolores formations, and conglomerates from one or the other of those formations. There are also many porphyries and some bowlders of a tuff-breccia, just as there are in the type section of the Ridgway till. These igneous and volcanic rocks were derived from an earlier series of intrusives and eruptives and are quite distinct in age from the later volcanics which constitute the mass of the present mountains.

The lithological character of this drift is distinctly different from that of the three Pleistocene drift deposits which are so commonly found in the foothill regions bordering the San Juan Mountains, and which are all present in this immediate district. The Pleistocene glacial deposits are characterized by the stones of the later Tertiary volcanics and usually contain very little that could not have been derived from those volcanics.

In one exposure near the junction of the two forks of White Creek on V Mountain a pebble-clay till is exposed which resembles the upper member of the Ridgway till at the type locality. This pebble clay contains many stones less than one-quarter of an inch in diameter and a few cobblestones and small bowlders. The best striae were found on stones that were taken from this pebble-clay phase of the till.

Beneath this exposure of Eocene till is the Mancos shale, and in this respect the conditions are identical with those at the northwest base of the range. Upstream from the best exposures of the till an andesitic rock cuts the Mancos shale and appears to be at the base of the till for some little distance. On the slopes above this deposit of till there are beautifully waterworn pebbles of pre-Cambrian rocks similar to those that characterize the Eocene glacial deposit. They appear to have come from the complete disintegration of a conglomerate. Such a conglomerate overlies the Ridgway till at almost all of the known localities.

This section is somewhat less satisfactory than many of those described in the first report on Eocene glaciation in the San Juan Mountains, for it is not at present overlain by the later Tertiary volcanics. The lithologic character of this deposit determines its age.

Reviews

Eocene Glacial Deposits of Southwestern Colorado. By WALLACE W. ATWOOD. Prof. Paper, U.S. Geol. Surv., No. 95-B, 1915. Pp. 13–26, pls. 4, figs. 11.

Glacial deposits of Eocene age were discovered in 1913 near Ridgway, Colorado, northwest of the San Juan Mountains. The nine exposures are scattered over an area of 20 square miles. The Ridgway till rests on the Mancos shale and is overlain by the Telluride conglomerate and San Juan tuff. The till is divided into two members. The lower is a bowlder till containing many striated stones, some very large. The upper till is a dark slate-colored clay, unstratified and containing only a few striated pebbles. The bowlder till is believed to have been deposited by glaciers heading in the region of the present San Juans. The pebble till may have been deposited by ice moving over extensive surface exposures of Mancos shale from the region of the West Elk Mountains to the northeast.

The paper closes with a summary of the distribution of pre-Pleistocene glaciation. An extensive bibliography is appended.

H. R. B.

The Yentna District, Alaska. By STEPHEN R. CAPPS. U.S. Geol. Surv., Bull. No. 534, 1913. Pp. 75, pls. 13, figs. 7.

This area lies along the southeast base of the Alaska Range in the drainage basin of the Yentna River, a tributary of the Susitna. The oldest rocks are a pre-Jurassic series of slates and graywackes. They are everywhere faulted and folded, and are intruded by igneous rocks ranging from granite to diorite. The intrusives are provisionally assigned to the late Lower Jurassic or Middle Jurassic. Older dikes of diabase and greenstone have been deformed and metamorphosed along with the slate series.

Next younger are rocks of Eocene age, consisting of sands, shales, gravels, and commonly some lignitic coal. Coarse stream gravels overlie the coal-bearing series. Evidence of the Tertiary age of the gravels was obtained. They were formerly regarded as Pleistocene.

They are probably equivalent to the Nenana gravels on the north side of the Alaska Range.

Pleistocene and recent glaciation are described. The present snow fields and glaciers are confined to the heads of the valleys and the higher portions of the Alaska Range.

Placer gold was first discovered in the Yentna district in 1905. The total production up to 1911 was $383,000. The gold is believed to have been derived from quartz veins and stringers associated with the intrusions in the slate and graywacke series.

The coal, in beds ranging from 3 to 12 feet in thickness, is a medium- to low-grade lignite.

H. R. B.

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THE ACTIVE VOLCANOES OF NEW ZEALAND

E. S. MOORE
State College, Pennsylvania

The northern island of New Zealand has, at the present time, five volcanoes which show more or less activity, besides a large number of others which have been active since Miocene time and are now dormant or extinct. This island has experienced much more volcanism during late geological time than the southern island, which consists largely of sedimentary and ancient metamorphic rocks. After traveling through North Island the writer was impressed by the simple statement of the Maori guide living near Mount Tarawera, who said, "New Zealand has been turned over and over."

The active volcanoes are White Island, in the Bay of Plenty, which displayed fresh activity in the autumn of 1914; Tarawera, near Rotorua, which suffered a terrific explosion in 1886; Ruapehu, which is in the solfataric stage and almost extinct; Ngauruhoe and Tongariro, which are in the solfataric stage, but still suffer explosive outbursts, those of Ngauruhoe being of considerable violence at times. The three last-named volcanoes are situated close together on the plateau in the central portion of the island.

There seems to be a close relationship among all these five volcanoes, as they are arranged along an almost direct line, indicating a zone of fissuring of immense proportions, known as the

Whakatane fault. Speight considers that this line continues from Ruapehu through Tonga and Samoa toward Hawaii along what he

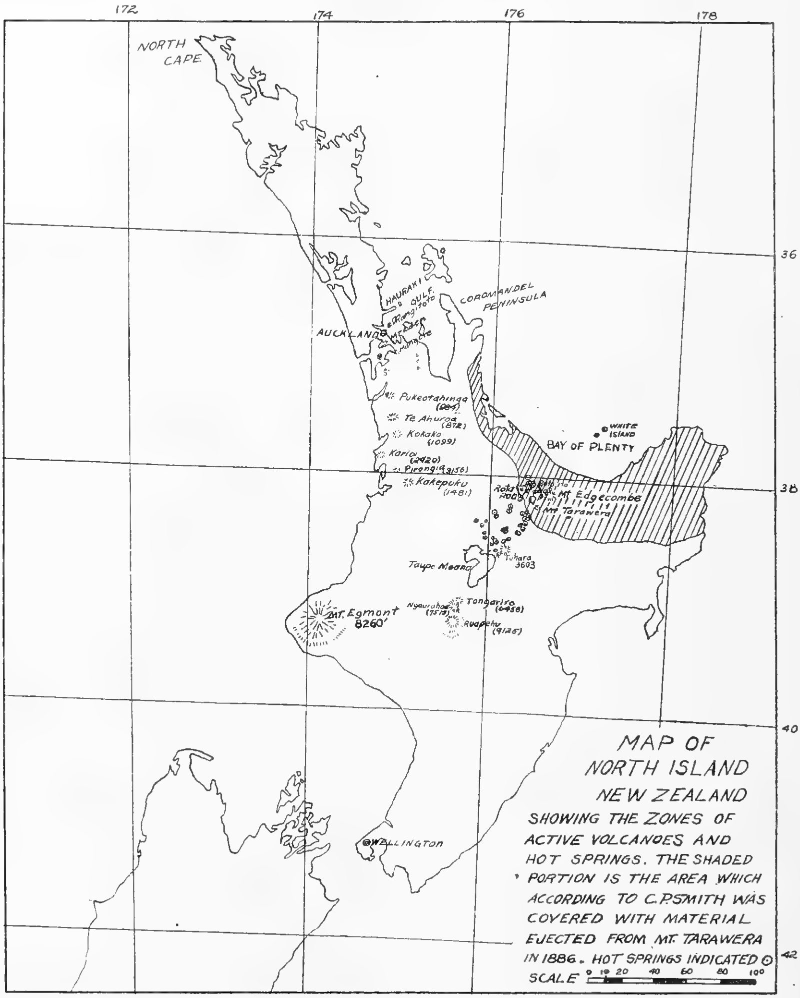


FIG. 1.—Map of North Island, New Zealand, showing the zones of active volcanoes.

calls the "Maori" line, since the Maoris probably migrated in a general direction along that line.[1] The "Samoan" and "Hawaiian"

[1] R. Speight, "Geology," *Report on a Bot. Sur. of the Tongariro National Park* (Dept. of Lands, N. Z., 1908), p. 9.

lines are supposed to cross the "Maori" line at their respective points of greatest volcanic activity. Running practically parallel to the fissured zone mentioned above, there is another zone containing numerous extinct or dormant volcanoes stretching along the eastern border of the island from the great Mount Egmont through the Auckland district, where over sixty craters, mostly of small magnitude, appear. There seem to have been, also, another line of disturbance and a great fault running from the north-central

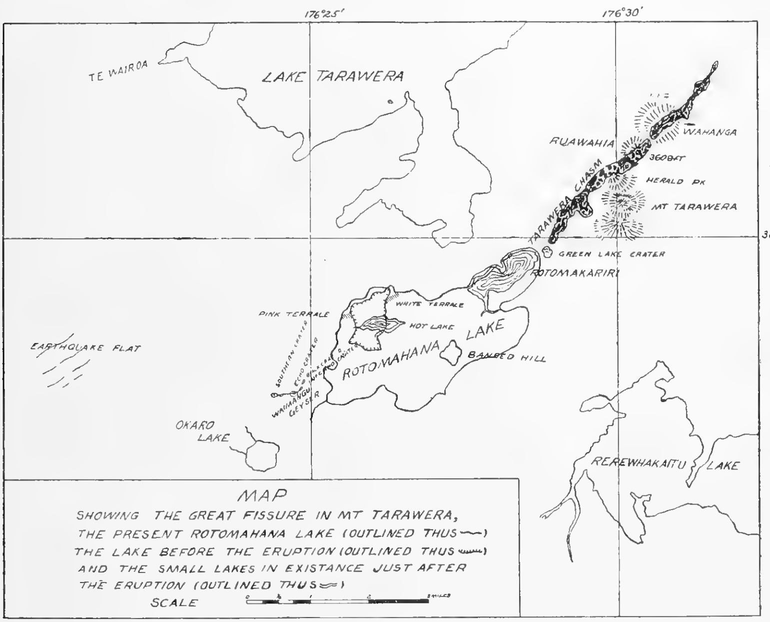


FIG. 2.—Map showing the course of the great fissure

part of the island nearly northwest to Hauraki Gulf and passing through the Waihi mining district. The prominent scarp of this fault may be seen from Morrinsville Junction in going from Auckland to Rotorua, and it is necessary to ascend this steep slope to reach the plateau before arriving at Rotorua. The streams descend rapidly over this scarp, which is a prominent physiographic feature of the landscape. This *graben* fault has aided in producing the lowland stretching from Hauraki Gulf toward the central portion of the island.

These major zones of disturbance run parallel to the main structural features of the islands resulting from the orogenic and epirogenic movements which produced New Zealand and the adjacent islands.

HISTORY OF THE LATER VOLCANIC ACTIVITY OF NEW ZEALAND

There seems to be a general agreement among New Zealand geologists that there were extensive post-Jurassic and pre-Mioeene movements, resulting in much folding and in bringing the islands nearly to their present geographical condition. The rocks formed up to this time indicate, according to Marshall,[1] that the present islands occupied a zone along the border of a continent now lost to sight. The folding raised the mountain ranges from the sea bottom and determined the major structures of the islands. There have been numerous oscillations since that time, but these have not materially altered the main structural features. Following these great disturbances, which may be correlated with those of America and Europe, there was inaugurated an important stage of igneous activity which became very prominent in the Miocene and has continued, more or less actively, since that time. There was some igneous activity during the Jurassic, and even then hypersthene-andesites, so common in later periods, began to make their appearance. Igneous rocks of this age are found, according to Park,[2] in the Hauraki Peninsula, while the andesites and rhyolites of the Canterbury district in South Island are regarded by some geologists as Jurassic.

The greatest period of activity seems to have opened in the Middle or Lower Miocene and to have extended into the Pliocene, and even into the Recent, in North Island. During the Miocene, which was also characterized by extensive orogenic and epirogenic movements, the main centers of activity were the Otago, Banks, and Hauraki peninsulas. The rocks of these areas generally rest on Omaru sediments, which are regarded as Early Miocene. In the Otago Peninsula the alkaline rocks were erupted at this time; in the Banks Peninsula, rhyolite, andesite, and basalt; and in the

[1] P. Marshall, *Geology of New Zealand* (Wellington, N. Z., 1912), p. 188.

[2] James Park, *The Geology of New Zealand* (Whitcombe & Tombs), p. 82.

Hauraki Peninsula, andesites followed by rhyolites. Probably the andesites extending north of Auckland up to North Cape were contemporaneous with those mentioned. The important gold veins of the Waihi mines are connected with this period of eruption as a later phase of the activity.

The great volcanic plateau occupying the central portion of North Island consists largely of rhyolite and pumice with the later extrusions of andesite and related rocks breaking through the rhyolites. The first evidence of the activity which produced the plateau is found in the rhyolite gravels of the Miocene, but the main eruptions are believed to be of Pliocene age because much of the pumice is found resting on early Pliocene strata and some is interbedded with them. The earliest igneous rocks of this plateau are, therefore, rhyolite and the latest andesite. As to the source of these acid rocks, there are factors which point to the Taupo area as the center of the eruption. While the writer did not have the opportunity of visiting Lake Taupo, he is convinced, after visiting other lakes in this region and reading descriptions of the Taupo basin, that these larger lakes in the central portion of the island are old craters modified by faulting. There is so much in common between such depressions and many of those of crater origin in the Hawaiian Islands that their origin can scarcely be in doubt.

The early andesite eruptions of Ruapehu, Tongariro, Egmont, Edgecombe, and related volcanoes occurred in the Pliocene, while the basanites of the Auckland area are probably of Pleistocene age.

PETROGRAPHICAL PROVINCES IN NEW ZEALAND

There is such a close relationship between the rocks of the Ruapehu–White Island and Egmont-Auckland zones that they may be justly regarded as belonging to one province. The rocks of Mount Egmont consist of hornblende-andesite and hornblende-augite-andesite; those of the Auckland region of basanite, poor in nepheline and probably lacking in this mineral in some cases; those of Ruapehu of augite-hypersthene-andesite; and those of White Island of hypersthene-andesite.

On the Coromandel Peninsula there were first eruptions of andesites of various types followed by rhyolite and these again by

hypersthene-andesite. It is probable that the great rhyolite extrusions of the central plateau were contemporaneous with those of the Coromandel Peninsula, and that the early andesite extrusions of this region did not occur in the plateau area. There are dacites in both areas.

Park considers that there are two other petrographic provinces in New Zealand of late Miocene or early Pliocene age, these being found on the Otago and Banks peninsulas.[1] In the former peninsula the rocks consist of an earlier series of phonolite, dolerite, trachydolerite, andesite, basalt, and basanite; and a later series, erupted on the eroded surface of the first, consisting of basalt with probably andesite and phonolite. Cutting the lavas of the first series are dikes of nephelite-syenite, augite-dolerite, and tinguaite. Professor Marshall, who has made a detailed study of this area, states that no regular order of eruption and no definite system of differentiation in these various rocks have, so far, been recognized.

On Banks Peninsula there was a period of rhyolite eruption followed, after considerable erosion, by andesites and basalts.

From the evidence presented there does not seem to be any regular order of eruption followed by rocks of the various types, except that in practically all cases there is a tendency for the volcanism to cease with the eruption of intermediate rocks, as andesites.

RUAPEHU, NGAURUHOE, AND TONGARIRO

These three large volcanoes are located near the center of North Island at the southern end of the rhyolite plateau. Their craters lie along a direct line, within a distance of less than fifteen miles, and if this line be projected northeastward it will pass also through Pihanga and Tauhara, volcanoes now extinct; then through Tarawera, Edgecombe, and White Island. Ngauruhoe is situated between the other two and almost on the side of Tongariro, in such a way as to indicate that it has arisen in the later stages of Tongariro as a subsidiary cone to this great volcano.

The rocks of all three of these volcanoes are similar, and consist of augite-andesite with augite-hypersthene-andesite. The early activity produced extensive flows of these rocks followed by

[1] Park, *op. cit.*, p. 147.

alternating lava flows and fragmental deposits of the same material. Ruapehu has not been in active eruption since early in the Recent period, but Ngauruhoe and Tongariro continue to suffer regularly weak outbursts. Evidence of this may be seen in Fig. 6. According to Marshall there has not been a flow of lava from a New Zealand volcano in historic times, but Park and Speight believe that in 1869 a lava flow escaped from the northwest side of Ngauruhoe and that the fresh appearance of this lava attests its recent origin.

FIG. 3.—Ruapehu (9,175 feet) from the Waiouru-Tokaanu road eight miles distant. Looking across the Onetapu Desert covered with volcanic sand and cinders.

Ruapehu.—This is an enormous mass of red to dark-gray lava and scoriae rising from a plateau region. Its height has been placed by various writers at 8,878 feet to 9,175 feet above sea-level, and the latter may be considered as the more correct figure. It has a large crater, approximately a mile in diameter, cut into on the south-southeast side by a great ravine, so that the rim of the crater consists of a series of prominent peaks. The crater is occupied by a glacier which surrounds a small, hot lake said to be about 600 feet in diameter. According to various reports, the water sometimes boils, and apparently it is the sulphur water from this lake which issues from the northeast side of the mountain.

The writer was unable to reach the lake on the date of his visit in October, 1914, owing to the steepness of the ice walls between the point where he reached the crater and the location of the lake, and from the brink of the crater no sign of it could be seen in the snow field within the crater.

The sides of the cone are covered with masses of andesite from the disintegrated lava flows and with fragments of large bombs. In some cases columnar structure is well developed in these flows.

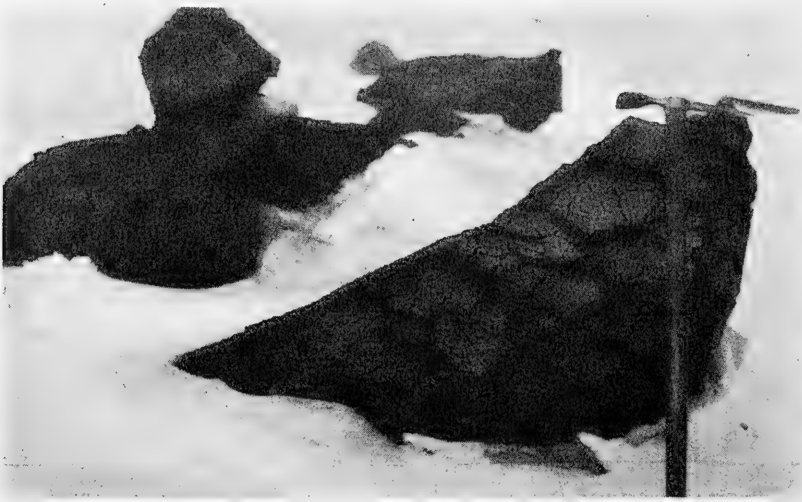


FIG. 4.—Bread-crust structure in a portion of a large bomb near the foot of Ruapehu.

In a fragment of a large bomb lying near the foot of the mountain and almost buried in the snow and cinders, an excellent example of bread-crust structure was found (Fig. 4). Small glaciers hang on the cone, extending, in some cases, as low as 2,000 feet below the crater rim.

Ngauruhoe.—This is a beautiful and symmetrical cone resting on an upland base which was probably largely developed by Tongariro before Ngauruhoe was of much importance. The elevation of this mountain is placed at 7,481 feet by S. P. Smith, and at 7,515 feet by Marshall. It is made up of a base of andesite flows on which rests the cone, consisting of alternating lava flows

and beds of tuff and agglomerate, with bowlders up to ten feet in diameter. Some interesting examples of flows which appear to have split, passing above and below beds of agglomerate and tuff,

FIG. 5.—Ngauruhoe from a point near the foot of Ruapehu. This view shows how the cone is built on an upland largely developed by Tongariro.

FIG. 6.—Ngauruhoe (7,515 feet) showing the usual cloud of steam and sulphur fumes rising from the crater.

may be seen on the east side of the cone (Fig. 7). These are found, on close examination, to be due to the viscous lava piling up and becoming brecciated in movement, so as to resemble a bed of tuff and agglomerate.

There was considerable snow and ice on the mountain when the writer visited it in the spring season, early in October, but this disappears in the summer and no glaciers remain here, as on Ruapehu.

FIG. 7.—Apparent splitting of lava flows. This seems to be due to the viscous lava becoming brecciated in movement so that it resembles tuff and agglomerate. The liquid lava then flows over the fractured layer.

The crater may be entered on the north side, where the rim is broken away and it is comparatively level on the bottom except for two mud volcanoes on the floor and a deep depression on the west side, the depth of which cannot be estimated since it is always full of fumes. The diameter of the main crater is about 500 feet and the height of the perpendicular walls on three sides of it was estimated at 200 feet in the higher portions. In the small crater there is a great deal of activity. Large clouds of steam mingled with sulphur dioxide rise continuously, and at times detonations like the crack of heavy rifle-fire may be heard. Considerable dust is intermittently shot up from this crater and, as seen from Fig. 8,

these explosions are occasionally quite violent. The explosion which threw out the cloud seen in the photograph, and which occurred on October 3, 1914, was said by some of the residents of Waiouru, twenty-five miles distant, who witnessed it, to be one of the strongest outbursts observed for at least two years. Up to the time this occurred, on the date mentioned, no sign of activity was seen around the mountain top, until at 9:30 A.M. this cloud was suddenly shot up about 1,000 feet before being drifted away

FIG. 8.—Cloud of dust and steam blown from Ngauruhoe, October 3, 1914. This explosion was much more violent than usual.

by a terrific wind, which was blowing at the time and prevented the cloud from rising to a great height.

Fumaroles occur around the steep walls of the main crater and well down the north side of the cone. On the northeast side of the cone was seen some reddish, highly vesicular, ropy lava, which has every appearance of being quite recent. As mentioned above, it has been stated by a number of writers that this stream was erupted in the year 1869, but not all New Zealand geologists are in accord on this subject.

Tongariro.—There are many features which make it appear that Ruapehu and Tongariro are major volcanoes with Ngauruhoe

subsidiary to the latter. Tongariro is an immense volcano, but with a cone of much less altitude than that of either of the others just described. The history of this mountain has been very

FIG. 9.—Looking from Ngauruhoe into the center of the crater of Tongariro and showing the Red Crater in the foreground.

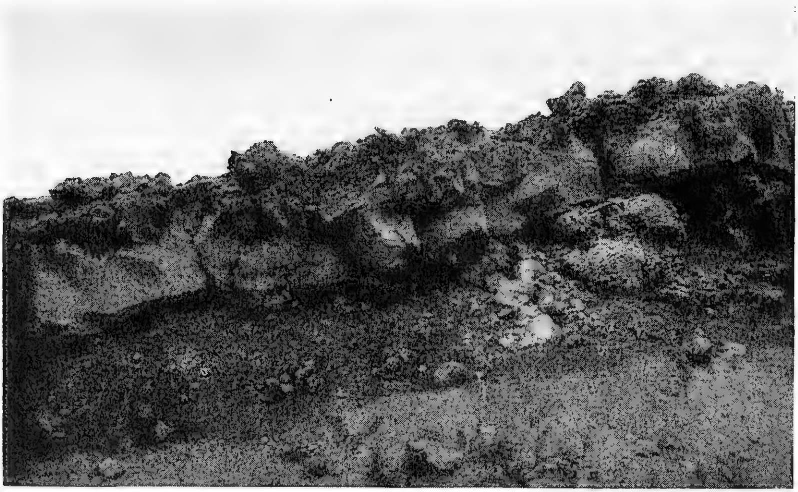


FIG. 10.—One of the later flows of andesite from Ngauruhoe

similar to that of Ruapehu. According to all the descriptions given, the lavas are andesites, mostly of the augite-hypersthene type, with small amounts of the hornblende-hypersthene type in some of the earlier flows. The cone consists of alternating lava flows and beds of scoriae. According to Speight[1] the height of the cone was greatly reduced by a terrific explosion, which was followed by extensive lava flows, and which blew 2,000 to 3,000 feet off the mountain. The crater rim now has a maximum altitude of 6,458 feet and is made up of a number of peaks surrounding several minor craters. One of these, known as the Red Crater because of the red color of the lava, is situated near the center of the main crater. Another, called Te Mari, lies on the northeast corner, and a third known as Tama is southeast of Ngauruhoe. Tama is believed to be part of the old crater rim, even if it lies beyond Ngauruhoe, and this is proof of the subsidiary character of the latter crater. All these craters are in the solfataric stage, but Te Mari is said by Speight to suffer explosive activity at times and to throw out ashes and stones. It was from this crater that the flow of andesite poured down through the forest on the flank of the mountain, and the conditions indicate that this eruption occurred at a comparatively recent date, although not within historic time.

In a depression on the main crater floor there is a small lake, called Blue Lake, lying at an elevation of about 5,500 feet. This lake, Te Mari, Red Crater, and Ngauruhoe all lie in almost a straight line, and they are apparently located on a fissure, or narrow zone of weakness, in the earth's crust. The Ketetahi Hot Springs are situated a little to the east of the line mentioned and well down on the northern flank of the mountain. They exhibit very strong thermal activity. Lying between Ngauruhoe and Ruapehu there are two small lakes, which probably owe their origin to some of the explosive activities of Tongariro.

MOUNT TARAWERA

Much has been written on Tarawera but many of the original works are out of print and unavailable. Reports have been prepared for the government bureaus of New Zealand by A. P. W.

[1] Speight, *op. cit.*, p. 11.

Thomas, Sir James Hector, and S. P. Smith, while other descriptions may be found in the works of Hutton,[1] Marshall,[2] and Park.[3] The special interest in this volcano lies in the great eruption of 1886, which produced results of much scientific, economic, and humanistic importance. The opening of the yawning chasm through the mountain, followed by the distribution of ashes over thousands of square miles of country with the accompanying destruction of life and property, is a matter of interest to every traveler who approaches this region.

Mount Tarawera was a small, nearly flat-topped mountain of rhyolite about 3,600 feet high and approximately 2,500 feet above Lake Tarawera lying at its base. There are on the mountain three prominences, known as Wahanga, Ruawahia, and Tarawera, the latter giving its name to the mountain as a whole. The structure was that of almost horizontal beds of pumice and flows of rhyolite, which had been poured out of some adjacent volcano or fissure, and which made up part of the rhyolite plateau in the central portion of North Island. Up to the time of the great explosion there was no evidence of a crater in the mountain, but it is situated in the zone of fissuring which runs from Ruapehu to White Island, and previous to the eruption there were numerous hot springs and geysers in the vicinity of the present Lake Rotomahana. It is close to Lake Tarawera, which has every appearance of being an old crater modified by local subsidence. The walls are steep and the water near the shore is deep in many places. The same condition exists in Lake Taupo and it may be concluded that all the steep-walled lakes in this region are of crater origin. The whole region lying between Tarawera and Rotorua is perforated with craters, hot springs, and geysers.

THE ERUPTION OF 1886

During the night of June 10, 1886, violent rumblings were heard and minor earthquakes experienced in the region surrounding the mountain. These increased in violence until about 2:00 A.M., when

[1] F. W. Hutton, *Report on the Tarawera Volcanic District*, Wellington, 1887. Also "The Eruption of Mount Tarawera," *Quar. Jour. Geol. Soc.*, XLIII, 1887.

[2] Marshall, *op. cit.*, p. 107.

[3] Park, *op. cit.*, p. 166.

the main eruption commenced and the great fissure began to open in the mountain, commencing at the north end in the hump called Wahanga. It passed through Ruawahia toward the basin now occupied by Lake Rotomahana and formerly containing the small lakes, Rotomahana and Rotomakariri. It opened under the lakes about 2:30 A.M. with a terrific roar and a cloud of steam which rose over 15,000 feet high.[1] This no doubt was due to the water rushing into the heated zone and producing a great explosion of steam. The result was the opening of a large pit, now occupied by Lake Rotomahana, while the débris was scattered widely over the country. The finer materials were carried out to sea over the Bay of Plenty, as indicated on the accompanying map (Fig. 1). It has been estimated that from the great fissure from 520,000,000 to 620,000,000 cubic yards of material was thrown out and this was spread over an area of almost 6,000 square miles, of which 1,500 square miles were damaged more or less severely from the agricultural standpoint. All habitations within four miles of the mountain were destroyed and 116 people killed. Most of these were natives, and while the majority of them were killed by the falling materials burying them, some around Rotomahana, where the natives often gathered, were literally carried away by the explosion. At Te Wairoa the buildings were crushed in and all vegetation destroyed or very severely damaged. There is still very little vegetation near the mountain, but it is interesting to see how quickly it has re-established itself at Te Wairoa, where the eucalypti are already fourteen to fifteen inches in diameter and other trees of less rapid growth are eight inches. The fern, like the braken of this country, establishes itself very quickly and flourishes on the acid soil. In many places the charred remains of trees are found, not only in the ashes of this eruption, but also in the ashes of earlier date.

The main eruption lasted about five hours, although the more violent part was probably over in less than an hour. Earthquakes continued for many days and there seems to have been some unusual activity in the hot springs around Rotorua. There have also

[1] According to S. P. Smith the measured height was 15,400 feet. "The Eruption of Tarawera," *A Report to the Surveyor-General*, New Zealand, 1887.

been reports of sympathetic action in Ruapehu, White Island, and other places along the volcanic zone.

Previous to the eruption of Mount Tarawera there were numerous hot springs and geysers in the area occupied by the present Lake Rotomahana, and the famous Pink and White sinter terraces were situated well within the border of the present lake.

THE GREAT FISSURE

As stated above, the eruption of Mount Tarawera began at the northern end of the mountain and progressed southward with the opening of an enormous fissure. This chasm is about $8\frac{3}{4}$ miles long, $1\frac{1}{4}$ miles wide in Lake Rotomahana, and 900 feet deep in the mountain. It is one of the most extraordinary openings to be found anywhere in the earth's crust (Fig. 11). Where it cuts through the mountain it takes the form of several deep, narrow craters in linear succession, separated by wedges of rock not blown out by the great explosions. The deepest opening is about 900 feet and it is about 1,000 feet wide at this point. In some places the crater walls are nearly vertical, but in others they have a gentle slope and can be descended to the bottom. There are a few small fumaroles, but they are no longer important. Along the brink of the chasm there is about 175 feet of highly colored, red and variegated scoriae deposited on top of the rhyolite materials thrown out of the fissure, but there is no evidence of a lava flow.

The fissure runs down the mountain side and through Lake Rotomahana, where it is 520 feet deep and has very steep walls in some places. It reached its maximum width here, where it is $1\frac{1}{4}$ to $1\frac{1}{2}$ miles wide. The present lake is about 4 miles long and 2 miles wide, and it covers the areas formerly occupied by the old Lake Rotomahana and Lake Rotomakariri. In the fissure, immediately after the eruption, there was a small lake called Hot Lake, but gradually the whole depression became filled with water. The explosion completely destroyed the Pink and White sinter terraces, which were located within the present basin rim, and fragments of them may be picked up for miles around where they are mingled with the other ejectementa from the fissure. There is still much thermal activity around Rotomahana, the name of which

FIG. 11.—The great fissure through Mount Tarawera. *A*, the north end; *B*, deep central portion; *C*, looking down fissure to Lake Rotomahana. In *A* and *B* the layer of red scoriae is distinctly seen along the brink of the fissure with the lighter rhyolite underlying it.

signifies "warm lake," and steam rises from many parts of the shore, especially near the northwest corner where the terraces and other hot-spring phenomena were most prominent before the eruption. The color of the water is a sort of dirty, greenish gray, like that of glacial streams, this hue being caused, no doubt, by the large amount of extremely fine particles of mineral matter suspended in the water.

Continuing westward the fissure passes through Black, Inferno, Echo, and Southern craters, all of which exhibit considerable

Fig. 12.—Lake Rotomahana, through which the great fissure passes from end to end. Looking westward from Mount Tarawera.

thermal activity at the present day. The basin of the extraordinary Waimangu Geyser, now inactive, is located on this line a short distance from Lake Rotomahana. This geyser became active in 1900 and continued more or less irregularly until 1908, when it ceased to act. It has been reported by various reputable authorities that it often threw water and mud to a height of from 1,200 to 1,500 feet. With the extinction of this geyser the surrounding springs became more active. The Waimangu "blow hole," situated southwest of the geyser orifice, blows hot water and steam for two minutes and is then quiescent for seven. In Echo Crater

the floor and walls are dotted with hot springs and fumaroles, and around some of these springs a great deal of iron pyrite is being deposited on pebbles, particularly in a spring called "The Frying Pan." The pyrite becomes disseminated in the sinter and to some extent it impregnates the thermally altered rhyolite. It seems to owe its origin to the reaction between H_2S and some iron salt, which in all probability is the chloride. The sulphide coats the pebbles with a black, smooth, waterworn layer which later tends to assume more nearly the appearance of typical pyrite. An assay was run on this pyrite deposit to determine the presence or absence of gold, and no trace of gold or silver was found. It seems probable that the pyrite in the sinters around Rotorua is of the same origin, and the large deposits of sulphur around the springs near Lake Rotorua appear to be due to the oxidation in the air of the H_2S so plentiful in these waters.

While the great fissure practically ends at the Southern Crater there are some smaller fissures and faults in Earthquake Flats which indicate the extension of the disturbance beyond the main fissure. There are lines of former movement which were again depressed a few feet.

DETAILED DESCRIPTION OF THE ROCKS OF MOUNT TARAWERA

This mountain was originally made up of interbedded rhyolite and rhyolite pumice, with streaks of dark gray to black, spherulitic obsidian running through the rhyolite. The bands often have the appearance of irregular dikes in the rhyolite, but they are probably due to the varying rate of cooling in different parts of the flows. The dark obsidian contains many fragments of the lighter rhyolite, and in some cases these have the appearance of being partly absorbed. This may be explained by the rhyolite fracturing on the cooled surface, permitting the liquid beneath to pour out around the brecciated fragments and to cool quickly. Good examples of this spherulitic obsidian were found on the road leading from Te Wairoa down to the landing on Lake Tarawera. Fragments may also be picked up among the débris from Tarawera, showing that the rock exists in the deeper beds in the mountain.

The rhyolite is quite fresh, brittle, and friable. Thin sections show that it contains a very deep dark-brown biotite, some augite, and, in one case, a grain of hypersthene, in addition to orthoclase, albite, and quartz which is very glassy and brilliant. The groundmass is usually mostly glass.

The obsidian consists of a brittle, dense, black glass, showing flow structure. It is full of spherulites from 0.05 mm. to 3.5 mm. in diameter. The glass contains also phenocrysts of green hornblende, orthoclase, and zonally built crystals of orthoclase and albite. The smaller spherulites consist of radiating needles of feldspar, while the larger ones are nearly solid glass around the center, with radiating dark lines and with concentric spheres

FIG. 13.—Bombs of andesite and basalt from Mount Tarawera. In two of them the light-gray cores of rhyolite may be seen ($\frac{1}{8}$ natural size).

becoming more distinct toward the exterior. These spheres are alternately brown and gray. The outer thick zone is brown and shows only a glass without crystal structure. The other zones show radiating small crystals of feldspar under the high-power microscope, but there is so little crystal structure that only a very slight darkening and brightening can be observed on rotating the section between crossed nicols, and there is almost no difference in birefringence between the spherulite and the surrounding glass. A distinct bending of the microlites in the glass around small spherulites may often be observed.

Bombs.—During the eruption of 1886 a considerable amount of intermediate to basic rock was ejected from the crater. It has been estimated that from 520,000,000 to 620,000,000 cubic yards of material was blown out of the great fissure. This was largely

rhyolite, but about 175 feet of dark, reddish-brown scoriae consisting of ashes, lapilli, and bowlders of vesicular and ropy lava lies along the brink of the great chasm through Mount Tarawera. The lava, which was the last to fall on the mountain, except some material from the basin of Rotomahana, welled up beneath the chasm and was caught in the big explosion. It was blown to fragments and thin layers of the fine material are mixed with the lighter colored tuff from the rhyolites around Rotomahana. It formed irregular masses of scoriaceous and ropy lava up to two feet in length, while it quite frequently formed spherical and oval bombs (Fig. 13). These bombs occur in great numbers around the foot of the mountain. The most peculiar are those with a core of rhyolite and an enveloping coat of andesite or basalt. They owe their origin to the fact that fragments of rhyolite were engulfed in the more basic lava, and when the explosion occurred these were hurled into the atmosphere with a rotary motion so that the viscous molten material became well wrapped around the core of solid rock. As a rule, this core is not exposed until the bomb is broken open. They all show the bread-crust structure well developed owing to the shrinking of the cooling, molten coat around the solid interior. In the specimens examined there is a sharp line of contact between the two rocks and there is no evidence of fusion of the rhyolite.

An examination of thin sections of the more basic rock showed in one case much dark, grayish-brown, vesicular glass containing numerous little laths of feldspar, a little augite, and a few small phenocrysts of enstatite. In another specimen the same minerals were found, with the exception of augite. In one small bomb the feldspars were identified from their extinction angles as anorthite and bytownite, and this same specimen contained traces of quartz, possibly due to absorption of some of the acid rhyolitic material before ejection. It was carefully examined for nephelite, owing to the reported occurrence of nephelite in the Auckland lavas, but it was found to be optically positive and to lack any sign of cleavage. Very small crystals of augite were present. The rock is a quartz basalt.

Dr. Marshall mentions hypersthene-augite-andesite in the bombs from Mount Tarawera,[1] but no hypersthene has been found

[1] Marshall, *op. cit.*, p. 102.

by the writer, the orthorhombic pyroxene in all cases being like enstatite.

From the description given it is evident that these rocks vary from andesite to basalt and that they represent a much more basic phase than any rocks previously erupted in the vicinity of Mount Tarawera. The sequence is very similar to that in all the other volcanoes in this petrographic province.

GLACIATION IN THE VOLCANIC ZONE

There has been much discussion in New Zealand in recent years regarding glaciation in North Island. Outside of the comparatively small glaciers on Ruapehu the writer did not see any evidence of glaciation. Around both Ngauruhoe and Ruapehu there were many bowlders which had grooves very similar to those often made by glaciers. It was surprising to find, however, that in practically all cases these were not due to glaciation, but probably to the action of one mass of rock falling on another when hurled from the craters. This was proved by the fact that the groove would often end abruptly against the wall in a re-entrant angle in such a way that it could not have been produced by glacial action.

FOOTHILLS STRUCTURE IN NORTHERN COLORADO

VICTOR ZIEGLER
Colorado School of Mines, Golden, Colo.

OUTLINE

INTRODUCTION

The area under discussion comprises a part of the foothills of the "Front Range" of Colorado, west and north of Denver, and extends from Morrison about 70 miles north to Fort Collins. No attempt will be made to discuss the stratigraphy of this district nor to describe any of the geological formations in detail; only the structural features will be emphasized.

STRUCTURAL FEATURES

THE FOOTHILLS MONOCLINE

The "master structural feature" of the foothills has been well described by Fenneman[1] in his discussion of the geology of the Boulder district, and also by Eldridge in the monograph on the

[1] *U.S. Geol. Survey Bulletin 265*, 1905, pp. 41–43.

geology of the Denver basin.[1] The following description is taken from the latter publication:

> The normal appearance of the foothills is that of a mountain mass of Archean rocks, fringed at an average distance of one half or three quarters of a mile by a sharp serrated ridge of Dakota sandstone, the valley between the two being occupied by the formations of the Trias and Jura. Above the Dakota come . . . . the Benton, the Niobrara—this generally constituting a second smaller reef outside the Dakota—the Pierre, the Fox Hills, and the Laramie, the basal sandstones of the Laramie again forming either a low roll in the ground or an actual comb of rock slightly projecting above the surface of the surrounding prairie. To the east of the Laramie . . . . appears in the southern portion of the area yet another comb formed by the conglomerates at the base of the Arapahoe series. Finally this is followed by . . . . the Denver formations.

To this description it is well to add that as a general rule the Lyons formation forms a prominent, though low, hogback in the strike valley to the west of the Dakota, and that in the northern part of the foothills the Archean-Fountain contact forms a prominent strike valley, and that here the Fountain is characteristically developed into a high, precipitous hogback, usually capped on its crest and dip slopes by the Lyons sandstone. Here also the Arapahoe and Denver formations are absent, and the Laramie lies almost horizontal twenty miles or more to the east of the foothills. In the southern part of the area the dips in the Fountain, Lyons, and Lykens average from 35° to 50°. These increase gradually eastward until they become vertical or even overturned in the Laramie, dips as low as 75° west being noted. Farther eastward these flatten within a few hundred feet from vertical into practically horizontal in the upper part of the Arapahoe or the base of the Denver.

No such variation is noted in the northern part of the area under discussion. West of Loveland dips of 40° are rare and occur only locally as the result of special conditions. The steepest dips occur here in the Dakota or Morrison. It is also worth noting that in the southern part of the area, where steep and overturned dips are met with, the formations have turned practically horizontal within two miles of the Archean contact—in one extreme

[1] *U.S. Geol. Survey, Monographs*, XXVII, 1896.

case (at Golden) even within 4,500 feet from the contact; while in the northern part of the area dips of 15° east are found as much as 10 miles east of the Archean sedimentary contact.

These contrasts in dips indicate that the foothills fold differs in shape and intensity over this area. The generally low dips near Fort Collins and Loveland indicate an ideal, fairly gentle, monoclinal fold, while the steep and overturned dips to the south indicate an S-shaped fold of pronounced type. The fold proper is well described by Fenneman[1] as follows:

> The master structural feature of this region is the great upturn of the strata against the mountain range. . . . . The first Archean belt west of the foothills is a dissected plateau . . . . from 6,500 to 7,000 feet above sea-level at its eastern edge, where it ends abruptly and is flanked by the Fountain sandstone. . . . . The height . . . . above the plains is nearly 1,000 feet. . . . . Five miles east of the base of the foothills the Archean surface is at least 9,500 feet below the surface, or 4,200 feet below the level of the sea. The real face of the granite plateau is therefore about 2 miles high, and this enormous rise is accomplished in 6 miles.

The opinion is also expressed that the greater part of the monoclinal flexure is the result of subsidence during the deposition of the various sedimentary formations, a conclusion passed on the assumption that the ancient shore line was located along the line of the present Front Range.

This generalization was, however, based on a small area of the foothills in which the characteristic structure is not well developed. Further, Lee[2] has proved since that all the Cretaceous formations up to and including the Laramie formerly were continuous over the present site of the Front Range. Consequently their present attitude must be due to orogenic forces, and the statement that "the process of mountain making gave to the granite plateau west of the foothills a comparatively small relative uplift above the plains" is erroneous.

A careful study of the dips and strikes of the formation south of the Boulder area and the reconstruction of a fold based on these dips as well as the occurrence of the lower formations as "inliers"

[1] *Op. cit.*, pp. 41, 42.

[2] *U. S. Geol. Survey*, P.P. 95-C.

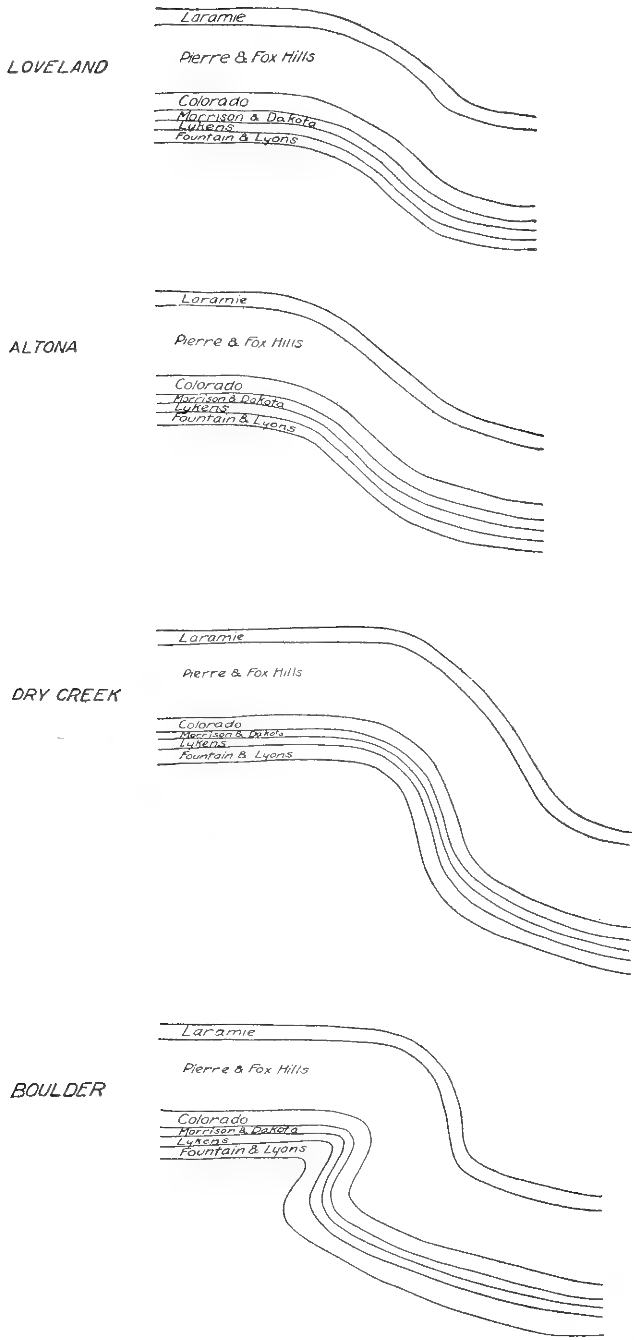


FIG. 1*a*.—Reconstructions of the original monoclinal fold of the foothills of the Colorado Front Range.

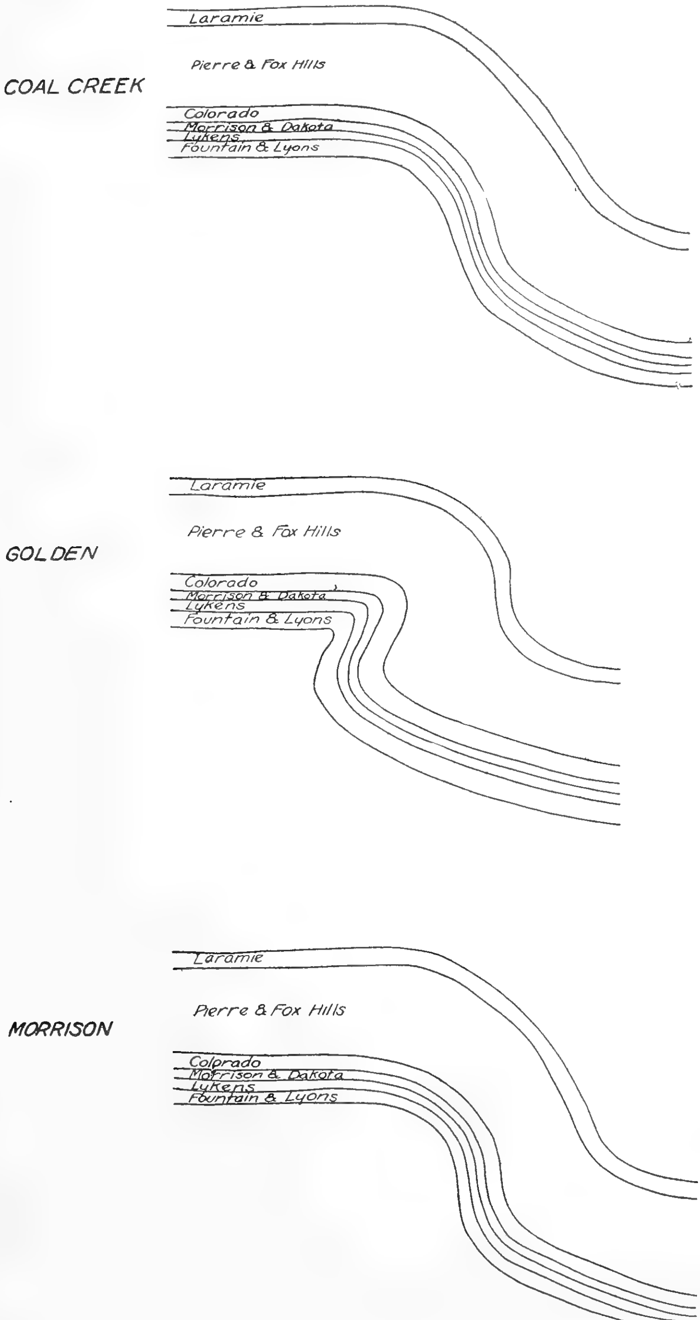


FIG. 1*b*.—Reconstructions of the original monoclinal fold of the foothills of the Colorado Front Range.

in the Archean some distance west of the foothills, as for example west of Colorado Springs and also west of Loveland, furnishes good reasons for the belief that the formations underlying the Dakota also extended over the Archean, or at least for a considerable distance westward. In areas undisturbed by special local conditions, the Fountain, Lyons, Lykens, and Morrison show as close an agreement in dips and strikes with the overlying formations as would be expected for conformable rock series; and all show beautiful parallelism in folding with the younger rocks. This would be a rather peculiar coincidence, not to be expected except in rocks simultaneously folded.

The accompanying diagrams show, drawn approximately to scale, reconstructions of the original monoclinal fold worked out from dips and strikes at the localities noted. In each case faults and other local irregularities which would unnecessarily complicate the fold have not been indicated. Their possible effect, due to displacements of parts of the fold and consequent introduction of anomalous dips and strikes, has been carefully considered in each case, and, where necessary, corrections have been made in the flexure of the monocline. These reconstructions are merely intended to show the variation in the shape and curvature of the foothills monocline in its major outlines (Fig. 1, *a*, *b*, pp. 718–19).

It is interesting to note that in older interpretations of the monoclinal fold in this region the overturn is located underneath the surface and not above the surface, as the present writer has drawn it. Considering no more than the present dip and strike relationship along an east-west line at such localities as Golden or Boulder, and considering these to be located on the same horizontal plane on the monoclinal fold, no other logical interpretation is possible. If, however, the variations in dip be carefully plotted along the axis of the fold, and if we carry in mind the fact that the dips as observed at Golden and Boulder represent different horizontal planes on the monocline due to the disappearance of thousands of feet of strata, the type of overturn postulated by the writer becomes necessary in order to explain observed conditions. This will perhaps be clearer after a discussion of the structure at Golden.

LOCAL UNCONFORMITIES (SO-CALLED "ARCHES")

Certain peculiarities in the distribution of the geological formations along the foothills, especially well developed near Golden and Boulder, have been explained as the result of unconformities due to local arching in the Cretaceous sea.

The Golden area.—The sketch map of the vicinity of Golden is, with a single correction, the map by Eldridge given in his report on "The Geology of the Denver Basin."[1] The areal distribution of the formation has been well traced in this map and has proved essentially correct, while the general features of the area in question (Fig. 2) have been well described in the following words:[2]

> The topography shows a marked variation from that normal for the foothills region in general. . . . . For mile after mile along the mountains the normal topographical features may be traced with unswerving regularity, but within the area to be described they undergo rapid change, and . . . . in the vicinity of the town of Golden they are lost to recognition. For a distance of over a mile north of the town, and an equal distance south of it, the Dakota hogbacks have completely disappeared; the low Niobrara ridges cease to exist at a point about a mile north of Bear Creek, not to appear again until the region of Van Bibber Creek, 10 miles to the north, is reached; the Laramie sandstones with their coal have gradually approached to within 500 feet of the Archean at Clear Creek, the variation in their strike from that of the Triassic and Dakota outcrops below being apparent to the most casual observer. . . . . The lines of stratification are delineated clearly upon the surface and display a distinct tendency to group themselves, with respect to direction, into two well-marked assemblages—the one embracing the formations of the Colorado and all below, and maintaining for the greater part of their extent the same parallelism to the general trend of the foothills which they have held beyond the affected area; the other embracing the Montana and younger formations, and though maintaining a parallelism of strike within themselves, nevertheless abutting against the older formations, in fact approaching the range proper in a broad, well-marked, and regular inward-sweeping curve, the center of its arch lying a short distance north of Clear Creek. The features just noticed again occur, in a minor degree and in a manner not at first liable to attract attention, in the relations between the Dakota and underlying beds nearer the middle of the area, where the beds of the younger formation lie across the edges of those of the older.

[1] *Op. cit.*, p. 83.

[2] *Op. cit.*, pp. 83–84.

Eldridge discusses each geological formation in great detail, and the care with which all structural features are described is worthy of special note. Rather than cite at length from this report the writer has arranged the pertinent data given in tabular form.[1]

STRUCTURAL FEATURES AT GOLDEN

Permo-Trias (Fountain, Lyons, Lykens)

1. Rapid disappearance of strata successively from the top downward as they approach Golden. Lyons disappears 1 mile north of Clear Creek, and $\frac{1}{2}$-mile south respectively. Lykens disappears about two miles north and south of Clear Creek.
2. Disappearance of Lykens is sudden north of Clear Creek; gradual to the south.
3. Discrepancy of 10° in strike with upper formations on disturbed area.
4. Normal thickness of Morrison is present where much of Lykens is missing.

Morrison

1. Missing for a distance of about $1\frac{1}{4}$ miles.
2. Discrepancy in strike (10°–15°) with younger Dakota and older rocks on disturbed area—especially marked in part north of Clear Creek.
3. Sudden disappearance of Morrison north of Clear Creek; gradual disappearance south.

Dakota and Purgatoire

1. Disappears from bottom up and top down.
2. Discrepancies in strike with rocks above and below on disturbed area.
3. More sudden disappearance on north side of area.
4. Marked crumpling on north side—frequent changes in strike, not shown by Laramie, which is only 600 feet to the east.
5. Normal dip 45°. Dips 90° and overturned over disturbed area.
6. Remarkable crumpling and recumbent folding south of Golden. (Not noted by Eldridge.)

Benton and Niobrara

1. Completely disappear from top downward. Benton absent for distance of about 5 miles; Niobrara for 9 miles.
2. Conformable in dip and strike to Dakota, but not to Montana on disturbed area.
3. After disappearance of Niobrara, overlain by successively higher Montana beds as it approaches Golden.

[1] *Op. cit.*, pp. 91–97.

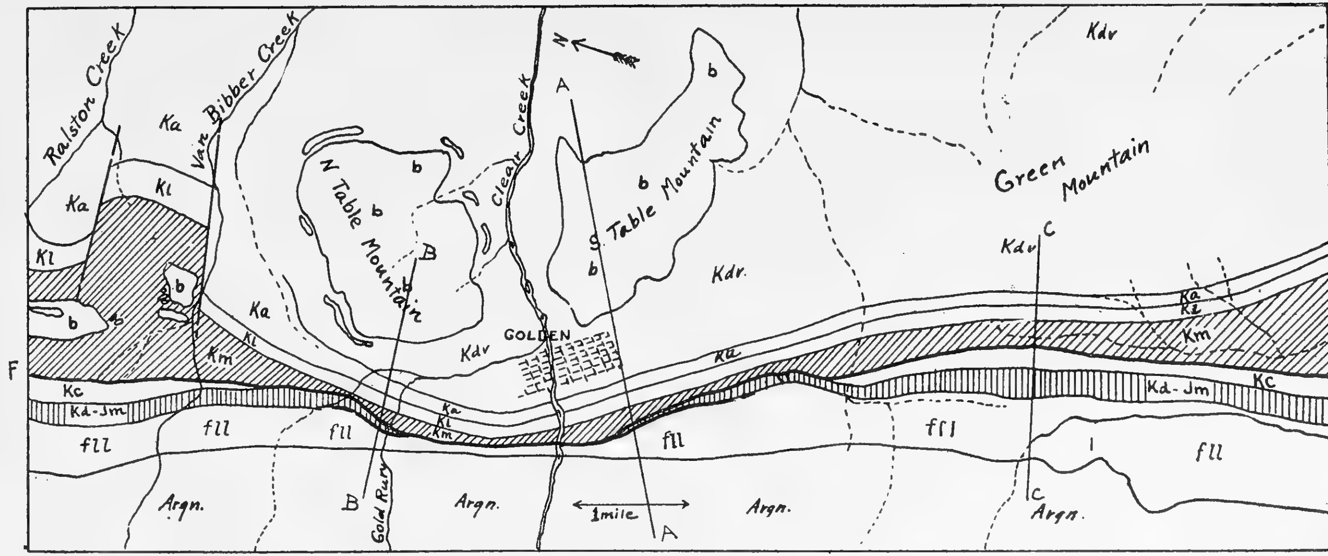


FIG. 2.—Sketch map of the vicinity of Golden. Heavy lines show faults

Argn	=Archean	*Km*	=Montana (Fox Hills and Pierre)
fll	=Fountain, Lyons, and Lykens	*Kl*	=Laramie
Kd-Jm	=Morrison, Dakota and Purgatoire	*Ka*	=Arapahoe
Kc	=Colorado (Benton and Niobrara)	*Kdv*	=Denver

Montana (Pierre, Fox Hills)

1. Pierre completely disappears from bottom upward. Absent for distance of about 4½ miles. Upper part of Fox Hills, only present at Golden.
2. Conformable in dip and strike to Laramie. Shows a discrepancy of 15°–20° in strike with older rocks.
3. Steepest dips on area at Golden—90° and overturned (80° W).

Laramie

1. Broad, sweeping curve by which it is gradually carried to the westward until at Golden it lies within 4,500 feet of the Archean.
2. No thinning.

Eldridge's Hypothesis of an "Arch" at Golden

The abnormal conditions tabulated above are all explained as the result of a series of unconformities at the horizons where these occur.

There is postulated a headland of anticlinal structure with axis perpendicular to the present trend of the foothills. This has been named the "Golden Arch" (Fig. 3). No attempt will be made to discuss the so-called "arch hypothesis" in detail. For such, the reader is referred to previous publications.[1] It will be noticed that the lines along which certain formations disappear are roughly parallel to the general strike of the foothills formations; and that as we approach Golden the formation to the west of such a line—that is, the older—disappears from the top down; while the formation to the east—that is, the younger—disappears from the bottom up. In the "arch hypothesis" such disappearance is explained as the result of the erosion of the older formations from the top of the rising headland, followed by a subsidence and a gradual overlapping of the younger formations against the sides and eventually over the top of this arch. The older formations are missing because of erosion; the younger, because of non-deposition.

Comments on the Arch Hypothesis: A number of points brought out in a former discussion as well as some additional data from field work seem to show serious weakness in the arch hypothesis. These points are in part facts described in detail by Eldridge and summarized above, in part facts discovered since, or at least not specifically noted by him, and in part certain fundamental

[1] *U.S. Geol. Survey, Monographs* (1896), XXVII, 91–97.

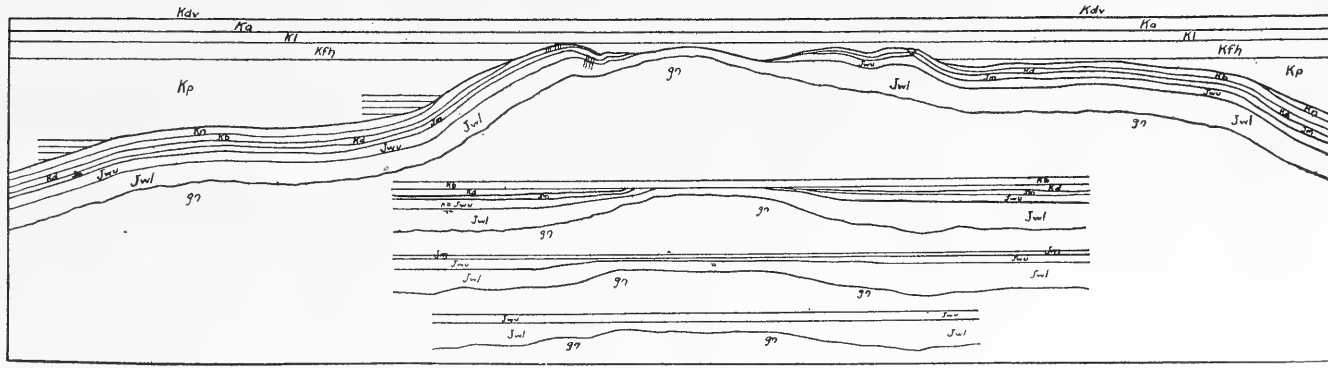


FIG. 3.—Stages in the development of the Golden arch (after Eldridge). Stages 1, 2, 3, and 4 are shown (from bottom up)

gn	=Archean	*Kn*	=Niobrara
Jwl	=Fountain and Lyons (Lower Wyoming)	*Kp*	=Pierre
Jww	=Lykens (Upper Wyoming)	*Kfh*	=Fox Hills
Jm	=Morrison	*Kl*	=Laramie
Kd	=Dakota (and Purgatoire)	*Ka*	=Arapahoe
Kb	=Benton	*Kdv*	=Denver

assumptions that appear unsound or at least unwarranted to the writer. The chief objections may be summarized as follows:

I. Objections based on facts:

1. The steepest dips occur where the formations disappear. For what reason, if their disappearance be due to an unconformity?

2. The greatest amount of overturning (60° W) is where the greatest thickness of strata is missing. The same question may be asked as for point No. 1.

3. Crumpling is common along the lines of the supposed unconformities.[1] Why?

4. Crumpling is relatively more severe on the axis of the supposed arch, that is, on the line where the greatest thickness of rock is missing. Why?

5. Crumpling is relatively more intense at those points where the formations disappear suddenly. Why this coincidence if their disappearance be due to erosion or non-deposition?

6. There is a remarkable coincidence of an association of maximum divergence of strike lines, steep and overturned dips, maximum crumpling, and the sudden disappearance of a formation. The simultaneous relationship of these to an unconformity is not clear.

7. There is an absence of shore facies in the sedimentaries. The existence of the Golden arch presupposes the existence of shore conditions, but none of the formations supposedly deposited against this arch show any change in lithological character upon crossing or approaching it.

8. No similar structures have been recognized elsewhere in the Rockies.

9. On the bluffs immediately to the south of Clear Creek the Dakota shows a dip of 60° westward, while less than 100 feet west the Fountain shows a dip of 40° eastward. These dips cannot be explained on the basis of an unconformity. (Not noted by Eldridge.)

[1] See also H. B. Patton, "Faults in the Dakota Formation at Golden, Colorado," *Colo. School of Mines Bulletin*, III, No. 1 (1905), pp. 26–32. A complete overturn through 180° is here described.

10. There are many minor strike thrust faults clearly shown, as well as dip faults with steep fault planes and a hingelike displacement toward the east—all of which are most pronounced in the immediate vicinity of Golden.

II. Objections based on interpretation:

11. The arch hypothesis presupposes the existence of a shore line immediately to the west. The work of Lee[1] has proved the former extension of the Cretaceous formations in a continuous sheet across the entire area of the Front Range. Hence this whole area must have been an epicontinental sea, and consequently a "headland" similar to the arch could not have been present at Golden.

12. Too much oscillation required of a small local area. Such rapid alternations of up and down movements are a strain on credulity.

13. It seems incredible that an elevation sufficient to prevent the deposition of any Pierre shale could have taken place at Golden, while a few miles to the north and south the true thickness of the Pierre (7,700 feet according to Eldridge) was deposited.

14. Another weak point in the arch hypothesis is the present attitude of the strata. These if considered in the plane of their bedding form a syncline with east-west axis over the crest of the supposed arch. The limbs on each side are dipping inward as much as 35°. None of the strata show any evidence of the original anticlinal folding to which they must have been subjected in order to form the "arch." A simple calculation will show that the arch requires an anticline with average dips of at least 10° in the older rocks for 10 miles north and south of Golden, while in the crest of the arch the dips must have risen as high as 30°. Eldridge, Emmons, and Fenneman are therefore driven to the conclusion that this arch was flattened out probably in Denver time and distorted into its present shape. This requires the sudden conversion of a persistently and rapidly rising area into a remarkably rapidly subsiding one, and requires a bending in the strata similar to that of a card bent back and forth between the fingers. This whole reasoning is not only laborious but also illogical.

[1] *Op. cit.*, p. 32.

The accumulative weight of the objections summarized above is so great that the writer unhesitatingly rejects the arch hypothesis as a possible explanation of the major structural features shown at Golden.[1] It is weak in its inherent fundamental assumptions, does not explain the many and peculiar coincidences in the facts observed along the line of the supposed unconformities, and is in several cases directly contradicted by dip and strike observations.

Proposed Explanation of the Structure at Golden: The geological conditions at Golden, outlined above, are best explained on the basis of extensive faulting practically parallel to the general strike of the formations. It is logical to believe that intense monoclinal folding of the "S" type shown to be characteristic of this part of the foothills could not be localized along a practically straight line without a decided tendency to form fractures and faults parallel to the general trend of the fold. On the accompanying geological sketch map of the vicinity of Golden the location of such faults is indicated by heavy lines, and it will be noted that these coincide with the lines of two of the unconformities of Eldridge in his arch hypothesis. The accompanying sections show in detail the faulting as postulated by the writer. In the case of section *A-A*, the double fault and its effect on the strata in the monoclinal fold is shown by a reconstruction of the latter in its original condition preceding each displacement (Figs. 4–7).

It will be noted that the faults are considered to have steep westward dips. The author has arrived at this conclusion from a study of the relationship of the course of the fault line to the topography, from a consideration of the character of the monoclinal fold, and the effect of the fault on the displaced rock formations. Ordinarily a thrust fault with dips as steep as indicated would be considered unusual, but we must carry in mind the fact that, in most cases of thrust faulting, lateral pressure is the dominant cause —as, for example, in the southern Appalachians. Here, therefore, thrust faults are as a rule characterized by flat dips. In the case of a monoclinal fold such as this, however, the maximum pressure

[1] Richardson, *U.S. Geol. Survey*, Folio 198, p. 11. It is of interest to note that both Lee and Richardson appear to doubt the truth of the arch hypothesis. In this connection see Lee, *op. cit.*, p. 32.

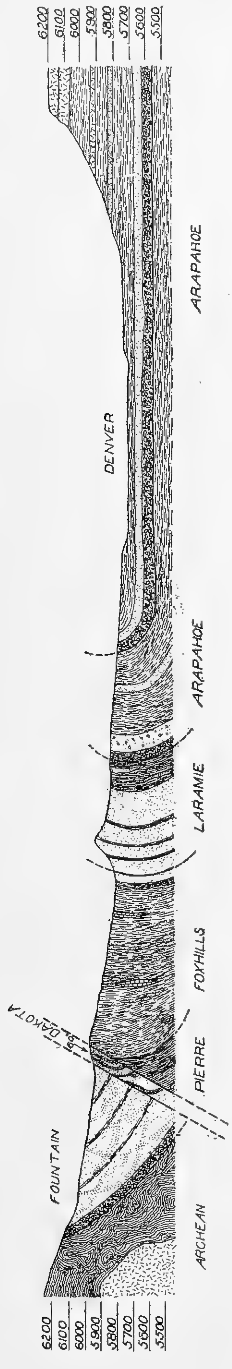


FIG. 4.—Structure section along east-west line through Golden

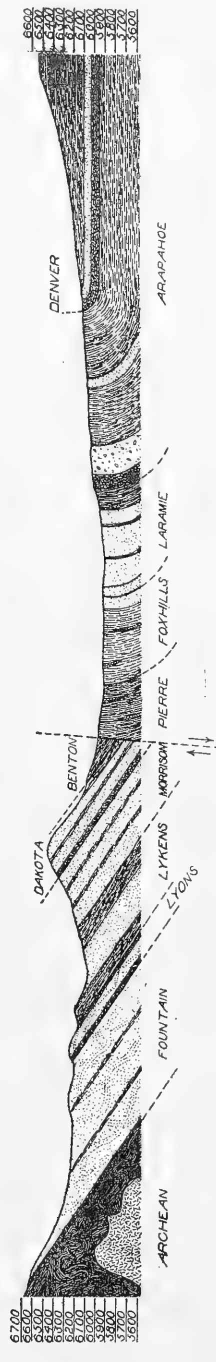
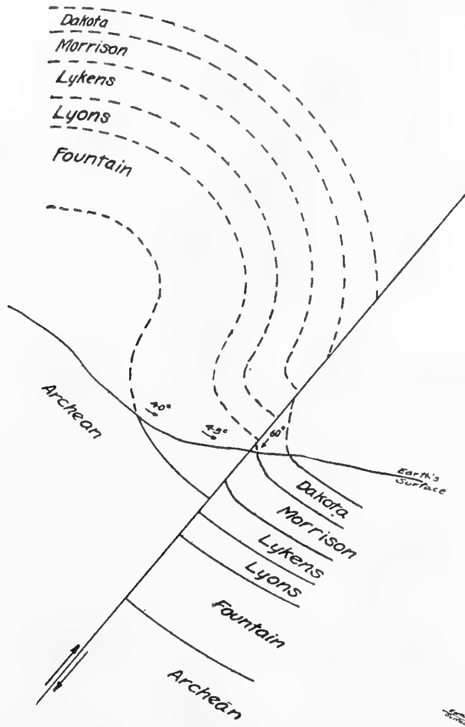


FIG. 5.—Structure section along east-west line, about four miles south of Golden

must have been nearly vertical and must have been manifest at the edges of the uplift in severely crowding the strata upon each other, owing to slipping and sliding on the steeply inclined Archean floor. Under these conditions the most logical planes of slipping would be the bedding planes, and the resulting faults would be strike faults with steep dips. The general dip and strike relationship shows normal easterly dips to be the rule in the older formations to the west of the fault plane, while the younger rocks to the east are characterized by overturned westerly dips. A consideration of the monoclinal fold will show that only a steep westward-dipping thrust fault as drawn by the writer can explain this relationship. Any eastward-dipping fault with overthrust from the east would bring younger horizontal rocks to rest upon



First Fault East of Tunnel House

FIG. 6.—Detail of first fault shown on Fig. 4.

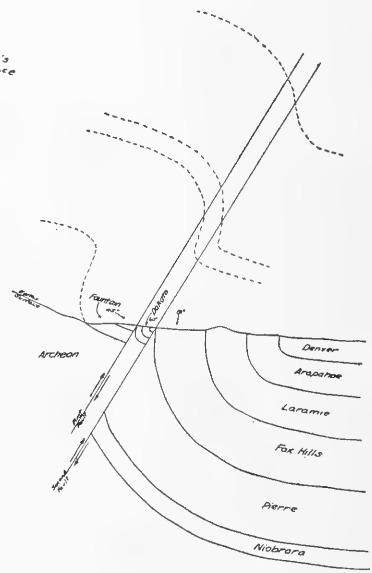


FIG. 7.—Detail of second fault (eastern one) shown on Fig. 4.

older steeply dipping ones, which is not the case. As will be seen from the sections, these faults are of the hinge type, with maximum displacements at Golden. This gradually decreases to zero toward the north and south.

All facts recorded by Eldridge and all facts observed by the writer accord perfectly with such an explanation. We should expect fault lines of this nature to be characterized by the crumpling and overturning of strata affected. The more sharply a formation is truncated the more evident the effects on its bedding planes should be. Maximum displacement and maximum disturbance should logically go hand in hand. The course of the fault plane and its position would determine whether a formation disappears from the bottom up or from the top down. As a general rule, with dips and strikes as observed, the formation on the west side of this fault plane should disappear from the top downward, while the formation on the east side should disappear from the bottom up. This is actually the case (Fig. 8).

Upon cursory examination the decided westward curve of the outcrops is somewhat surprising and seems to suggest that the eastern block represents the upthrow side. This is, however, not true, and the inward curve is the combined result of the gradual steepening and eventual overturning of the monoclinal fold as we approach Golden, and the displacement along the westward-dipping fault surface.

The actual inward sweep of the strata resulting from the writer's interpretation of the structure can readily be approximated as follows: The total thickness of strata actually cut out at Golden is about 10,000 feet. Therefore, the lowest bedding plane on the Fox Hills remaining at Golden must have been located at least 10,000 feet higher than its present position on the monocline before faulting. To this must be added the difference in elevation between the top of the Archean and the Fox Hills today (at least 1,200 feet) and a certain amount to allow for folding, hence 12,000 feet may be considered a safe estimate as to the minimum amount of throw necessary to bring the base of the Fox Hills from its original location in the monocline to its present position. A vertical drop of 12,000 feet on a fault plane dipping 55° westward will result in a

westward travel of 8,000 feet on the horizontal plane. The result of the displacement alone will be a decided westward heave in any

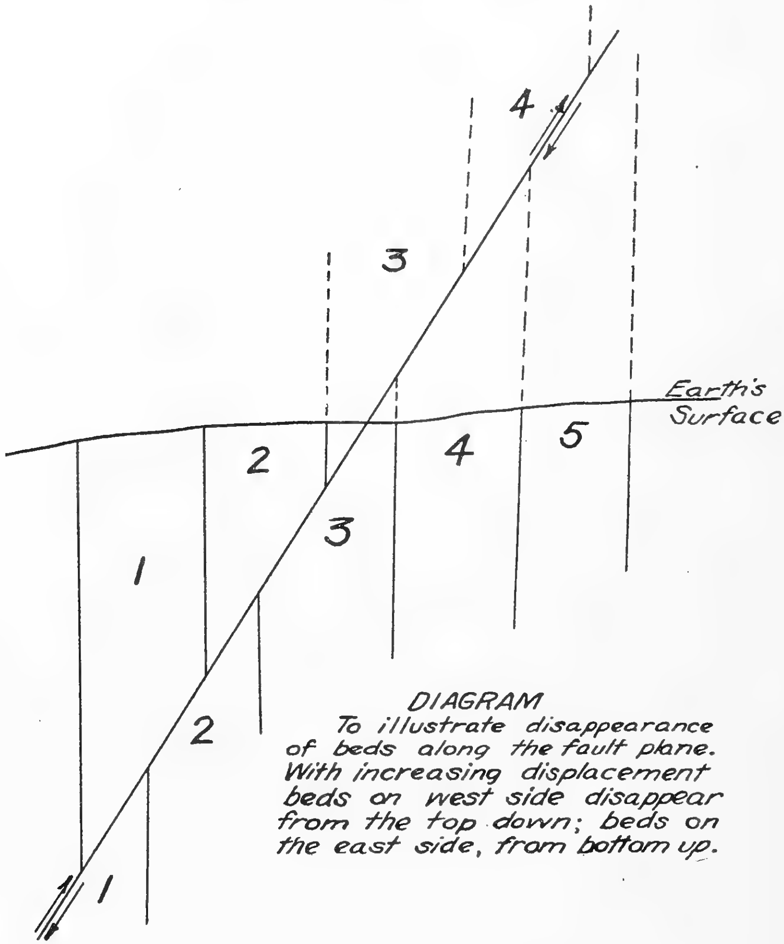


FIG. 8.—Diagram illustrating the disappearance of beds along the fault plane. Older beds (on left) disappear from top down; younger beds (on right) disappear from bottom up.

outcrop, and, since the amount of westward travel is dependent upon the amount of throw, each outcrop should show a progressively larger travel toward the west as we approach Golden.

This westward travel of 8,000 feet, due to the fault, will be augmented considerably by the change in the character of the monoclinal fold. As has been shown above, the monocline north and south of Golden is normal, gradually steeping and eventually overturning as it approaches Golden. The natural dip of the formations in the normal parts would, therefore, carry their outcrops far to the east of the steeper and overturned parts of the monocline, which, added to the effect of the faulting, is undoubtedly sufficient to account for the present situation of the various formations.

In connection with the writer's interpretation the following statement from Marvine[1] referring to the condition at Golden is of interest: "Some of the facts at hand indicate that a peculiar fault, depending on the nature of the sharp fold, and possibly connected with the lava near by, may have caused the present appearance."

The true nature of the fault was not realized by Marvine, for he also states "this may be caused . . . . by a fault which has pushed the higher portion of the series westward over the upturned edges of the lower portion, thus concealing much of the latter." Such a displacement is, however, incompatible with the data at hand and was hence rejected by later workers.

It is also of interest to note that Lee and Richardson[2] appear to doubt the existence of local unconformities in the foothill region. Dr. Patton also states in personal conversation that many of the phenomena observed by him in the foothills appear to be incompatible with the arch hypothesis.

The Boulder area.—The same structural peculiarities are shown at Boulder as at Golden, but not developed to the same remarkable degree and differing in some minor detail. Eldridge,[3] and subsequently Fenneman,[4] studied this area in detail and developed an explanation in every respect similar to that advanced for the conditions at Golden (Fig. 9). Elsewhere[5] the writer

[1] *Hayden Survey*, VII (1873), 137, 138.

[2] See Lee, *op. cit.*, p. 32; Richardson, *U.S. Geol. Survey*, Folio 198, p. 11.

[3] *U.S. Geol. Survey, Monographs*, XXVII, 105–14.

[4] *U.S. Geol. Survey Bulletin 265*, pp. 54–66.

[5] *Colo. School of Mines Quarterly*, April, 1917.

has discussed the Boulder area in detail and has shown that in this district also it fails to account for the local structural features and is fundamentally as unsound here as it is at Golden.

The accompanying sections show the writer's interpretation of the structure at Boulder. Here, as at Golden, steeply dipping strike faults have taken place parallel to the general trend of the foothills monocline, which are responsible for the disappearance of some formations and the notable decreases in thickness exhibited by others. The writer will not attempt to discuss these faults in

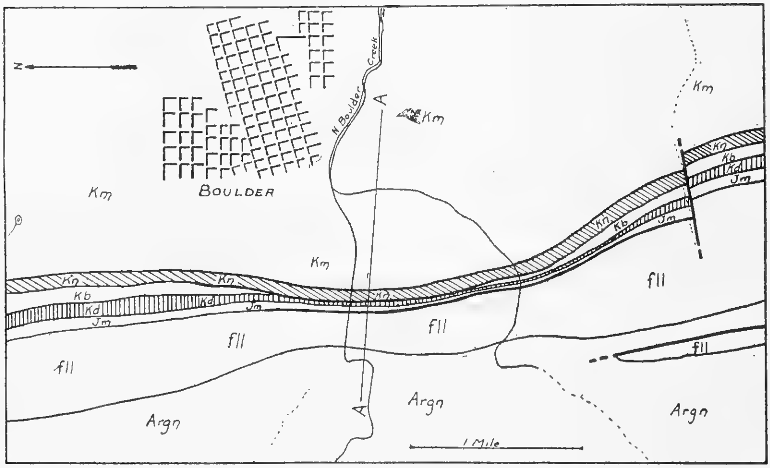


FIG. 9.—Sketch map of vicinity of Boulder (after Eldridge). Heavy lines indicate faults. For symbols, see Fig. 2.

detail. They resemble in every respect the faults at Golden and affect the strata in a similar way, but to a lesser extent. They are in absolute harmony with the manner of disappearance and thinning of the various formations, with observed dip and strike relationships, and do not postulate the extreme local subsidences and elevations required of the older explanation (Fig. 10).

Minor structural features.—Much minor faulting and folding, some of it of eccentric type, characterizes the great monoclinal uplift. Elsewhere[1] the writer has discussed this in some detail, especially for the purpose of bringing out the relation existing

[1] *Op. cit.*

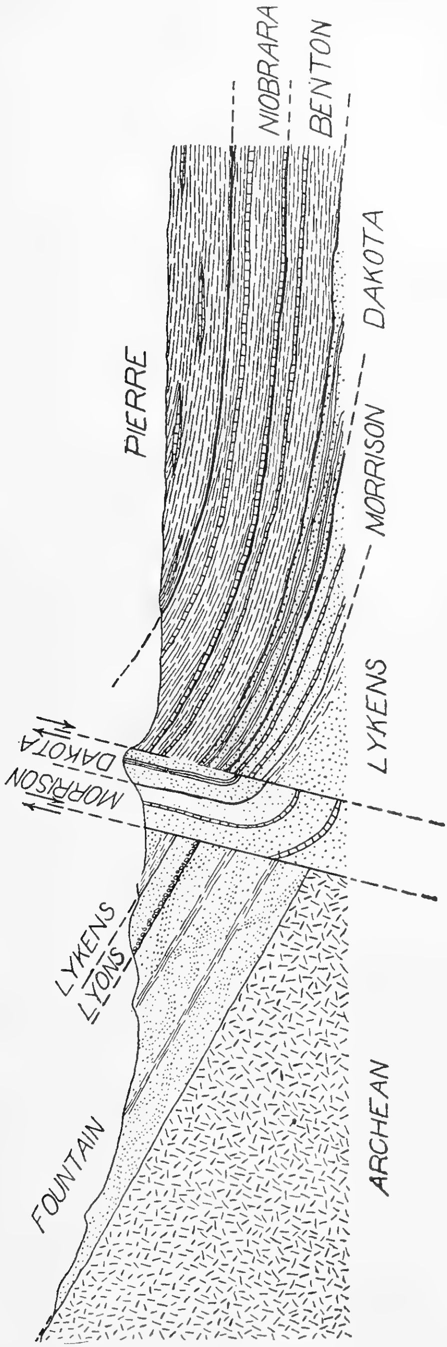


FIG. 10. East-west structure section through city of Boulder

between these minor structures and the huge thrust faults here described (Figs. 11–15).

Minor Folds: Two distinct types of minor folds can be recognized, *folds en échelon* and *drag folds*. The former pass practically invariably on their west flank into eastward-dipping faults with strikes nearly parallel to the axis of the fold. They represent

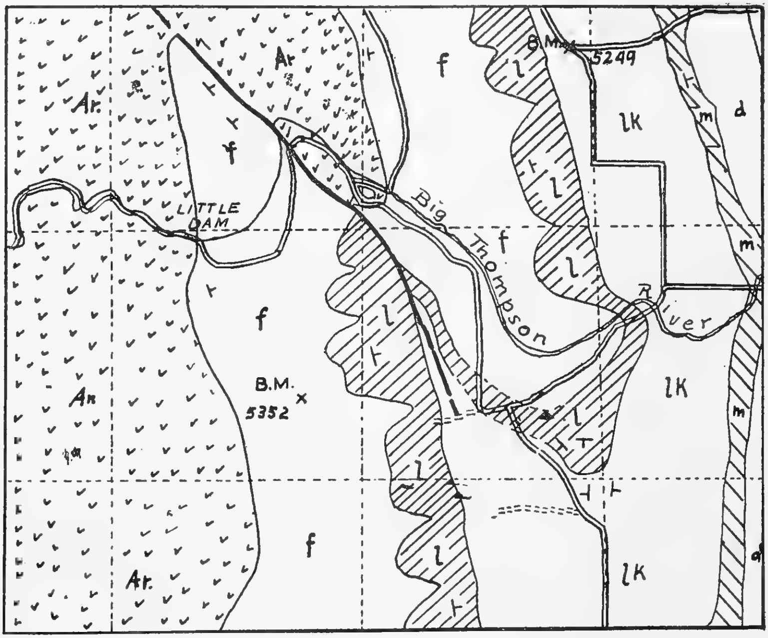


FIG. 11.—Geological sketch map of area on Estes Park road west of Loveland, showing characteristic fold *en échelon* and accompanying thrust fault. Section lines are indicated.

minor wrinkling, with overthrusts from the east subordinate in amount to the main monoclinal uplift and faulting. Other folds, noted especially in the shale series, represent adjustments by incompetent layers to stresses incident to the formation of the uplift.

Minor Faults: Both strike and dip faults are numerous, especially in the structurally disturbed areas at Golden and Boulder. They are all of slight displacement. They do not antedate the

uplift of the monoclinal fold, as stated by Eldridge, Fenneman, etc., but represent minor fracturing and slipping attendant upon, and consequent to, the formation of the main monoclinal uplift and its master-faults.

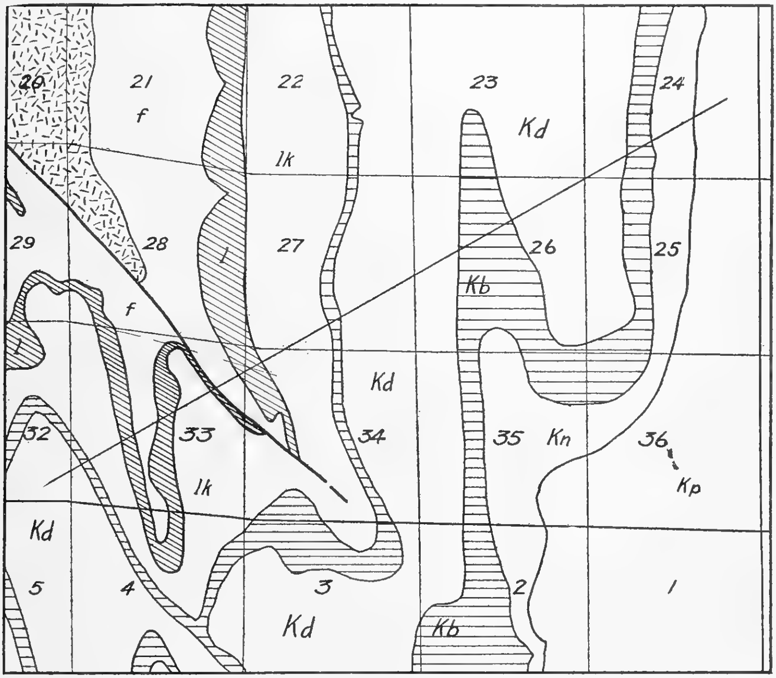


FIG. 12.—Geological sketch map of southwest corner of Loveland quadrangle, showing folds *en échelon*. For symbols, see Fig. 2.

SUMMARY

The master-monocline.—It has been shown by a reconstruction of the original foothills fold from observed dip and strike relationships that this represents an ideal monoclinal fold in strata originally continuous over the entire area of the Front Range, which gradually steepens and eventually overturns as it approaches Boulder and Golden. Contrary to former interpretations and general belief, the maximum overturn is above the earth's surface.

The main faults.—It has definitely been proved that the structural irregularities at Golden (and Boulder) cannot be explained

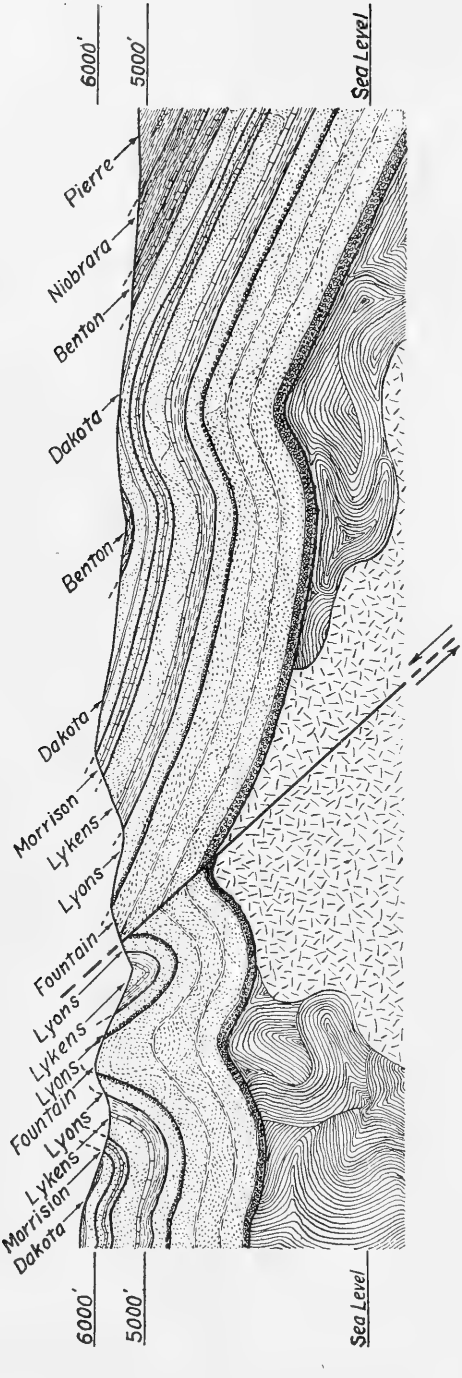


FIG. 13.—Section along line indicated on Fig. 12

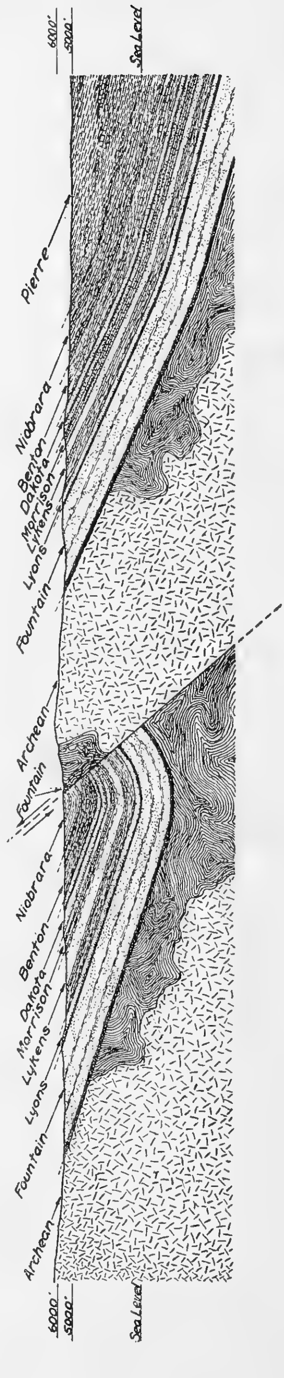


FIG. 14.—Huge fold *en échelon* and fault west of Loveland, east-west section, through Mt. Milner

as the result of repeated local arching and contemporaneous erosion, as attempted by former workers in this field. An alternative interpretation has been advanced by the writer which

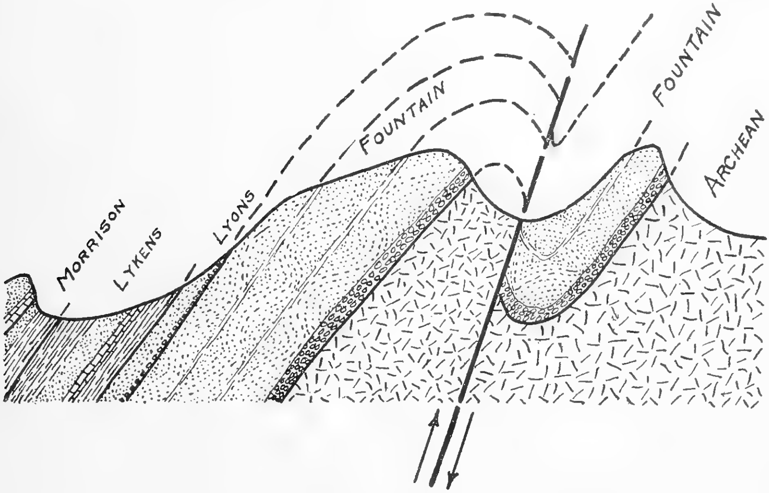


FIG. 15.—Fold *en échelon* of the Twin Peaks at Boulder. East-west section

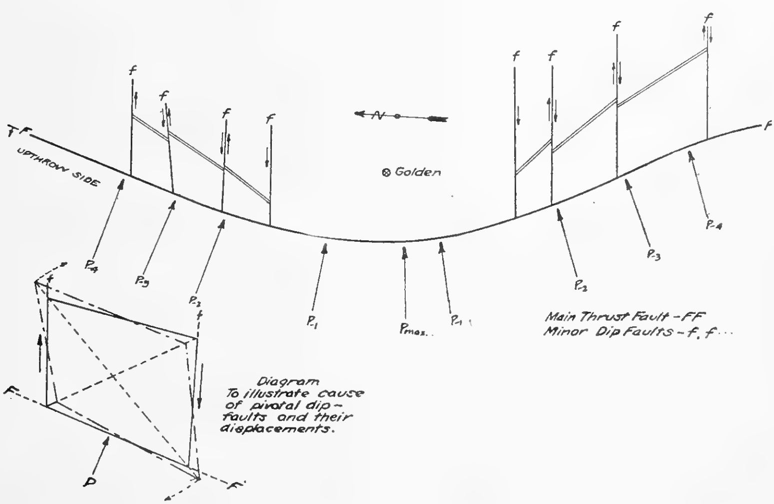


FIG. 16.—Diagram to illustrate the displacement of the dip faults and their relation to the large thrust faults at Golden. Small diagram shows distortion of interfault block due to pressure causing the main fault. The small arrows indicate the direction of displacement of interfault blocks.

postulates the presence of extensive strike faults with steep westerly dips and overthrust from the west. This interpretation is shown to be free from the inherent weaknesses of the older so-called arch hypothesis, and to be in perfect accord with all observed geological features.

Conclusion.—The formations represented in this area of the foothills range in age from Permo-Carboniferous to Paleocene. The Cretaceous formations certainly, the older probably, extended formerly over the entire area of the Front Range. At the close of Arapahoe time and during early Denver time the area to the west of the foothills rose, and the sedimentaries were folded into a normal monocline with average eastward inclination of about 45°. Locally (as at Golden and Boulder) excessive overturning occurred, accompanied by fracturing, and resulting in extensive overthrusts from the west along steeply dipping fault planes. Minor strike faulting, and dip faulting with hingelike displacements, as well as drag folding, accompanied and followed the major uplift and faults. The natural buckling and wrinkling of strata, where the pressure on the monoclinal fold was not intense enough to cause huge strike faults, resulted in the formation of folds *en échelon*, with their attendant overthrust faults from the east. The exact time of the uplift cannot be closely determined, except that the basal beds of the Denver are involved in the folding and that the composition of the upper beds of this formation shows that erosion had entirely cut through the sedimentary series over the site of the Front Range at the time of their deposition.

The sincere thanks of the writer must be expressed to Dr. H. B. Patton for advice and helpful suggestions in the preparation of this paper.

ON THE GEOLOGY OF THE ALKALI ROCKS IN THE TRANSVAAL

H. A. BROUWER
Delft, Holland

CONTENTS

INTRODUCTION

In June 1910 I studied the geology of the occurrences of nepheline syenites in the Transvaal, and the results were published in the same year in a paper, "Oorsprong en Samenstelling der Transvaalsche Nepheliensyenieten," which contains a contribution to the geology and a petrographical description of the nepheline syenites and various allied rocks. In the following pages some geological questions will be treated more in detail and the main results of recent work of the Geological Survey of South Africa are added.

I am much indebted to Professor G. A. F. Molengraaff, of Delft, who placed his collection of rocks at my disposal, while the text has been much improved by his valuable suggestions; and also to Professor A. Lacroix, of Paris, the rock material being studied for the greater part in his laboratory.

For assistance during my stay in South Africa, my best thanks are due to the staff of the Geological Survey, particularly to Mr. A. L. Hall, who furnished some rock specimens from Rietfontein [451] and Spitskop [463].[1]

As a guide to the stratigraphy and the geological dates mentioned below, a table of the Transvaal formations is entered (see Table I).

IGNEOUS COMPLEX OF THE BUSHVELD

The nepheline syenites of the Transvaal make part of a complex of igneous rocks, which is intrusive as a laccolith or laccolithic sheet between the upper strata of the Transvaal system and the strata of the unconformably overlying Waterberg system.

The laccolithic character of this complex was recognized by Molengraaff,[2] who grouped them under the name "plutonic series of the Bushveld";[3] it includes igneous rocks, which have a high soda content as a common character. The name used by other authors, "igneous complex of the Bushveld" or "Bushveld igneous complex," has the same signification and can be considered as the official one, because the Geological Survey of the Transvaal has adopted it.

PLACE OF THE MAIN TRANSVAAL LACCOLITH

The western boundary of the part of the complex in the Central Transvaal, which has been uncovered by erosion, is found nearly 15 km. to the west of the Marico River; the eastern one, nearly 25 km. to the west of Lydenburg; the medium breadth is nearly 100 km.

But probably it covers a much larger area; at least it appears again between the Magalakwin River and the sources of the

[1] Throughout this paper numbers in brackets refer to official designations for farms in South Africa.

[2] G. A. F. Molengraaff, "Géologie de la République Süd-Africaine du Transvaal," *Bull. de la Soc. Géol. de France*, Série 4, T. I, 1901, p. 13.

[3] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 42.

Matlabas and to the north of the Palala Plateau, where it extends to the north to near the Limpopo, nearly 30 km. to the south of the northern boundary of the Transvaal.[1]

BOTTOM OF THE LACCOLITH

The bottom of the laccolith is formed everywhere by the upper strata of the Pretoria series, generally consisting of Magaliesberg quartzite.

Therefore the rocks of the laccolith in the Central Transvaal are for the greater part surrounded by the upper Pretoria strata; in the strata of the Transvaal system, which dip everywhere toward the central part of the complex, the dip of the strata decreases when the distance from the complex increases. Because the Magaliesberg quartzites of the Pretoria series have specially resisted erosion we now see them as a ridge surrounding the complex.

We see that the bottom of the laccolith is determined, but the the place of the roof of the laccolith is uncertain.

ROOF OF THE LACCOLITH

The part of the laccolith, which has not been uncovered by denudation, is covered by the strata of the Waterberg system and partly by the younger strata of the Karroo system. Between the basal conglomerate of the sandstone series of the Waterberg system and the underlying rocks of the Bushveld complex we sometimes find a series of felsitic rocks, which other authors have considered as being directly connected with the deep-seated rocks of the laccolith, but which the Geological Survey of the Transvaal regards as a lower division of the Waterberg system.

The Waterberg system then includes:

Waterberg system	Upper Division	Sandstones, grits, and conglomerates
	Lower Division (Volcanic series)	Felsites and allied volcanic rocks with interbedded shales

[1] G. A. F. Molengraaff, "Geologische Aufnahme der Süd-Afrikanischen Republik," *Jahresbericht über das Jahr 1898*, Pretoria, 1900; G. G. Holmes, "Some Notes on the Geology of the Northern Transvaal," *Trans. Geol. Soc. South Africa*, VII (1904), 51–56.

The roof of the laccolith would, then, not be formed by the sandstone series of the Waterberg system but by the volcanic

TABLE I

TABLE OF THE GEOLOGICAL FORMATIONS OF THE TRANSVAAL[1]

Main Igneous Intrusions	Sedimentary Rocks			Age
	Superficial Deposits			
	Unconformity			
	Karroo system	Upper Karroo	Bushveld amygdaloïd	?
			Bushveld or Buiskop sandstone	?
		Middle Karroo	Highveld or Beaufort series with coal measures	Permo-Carboniferous
		Lower Karro	Ecca shale series	
			Dwyka conglomerate or tillite	
Bushveld igneous complex intruded as an unconformational laccolithic sheet between the strata of the Pretoria series and those of the Waterberg system	*Waterberg system*			
	Unconformity			
	Transvaal system		Pretoria series	Probably pre-Devonian
			Dolomite series	
			Black Reef series	
	Unconformity			
	Ventersdorp or Vaal River system			?
Old grey granite.—The exact age of the intrusion or the intrusions of this granite is not yet known. The intrusion, however, took place certainly after the deposition of the rocks of the Swaziland system and before the deposition of the rocks of the Transvaal system	Unconformity			
	Witwatersrand system	Upper division, containing the famous auriferous Main Reef series		?
		Lower division		?
	Unconformity			
	Swaziland system			?

series, in which sometimes red granites can be seen clearly intrusive. But the question of the mutual relation between the rocks of the

[1] Cf. G. A. F. Molengraaff, "The Deposits of Iron Ore in the Transvaal," in *The Iron Resources of the World* (Stockholm, 1910), p. 1060.

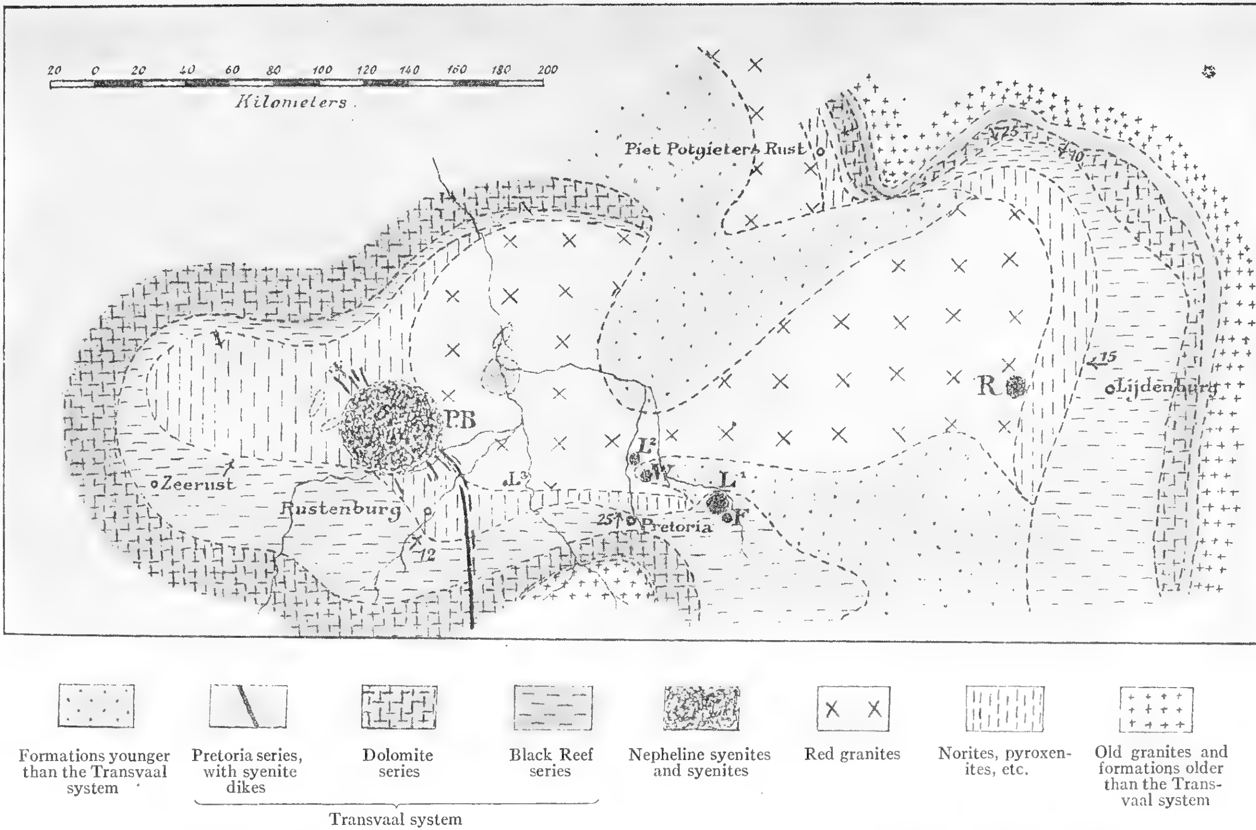


FIG. 1.—Geological sketch map of the Central Transvaal with the occurrences of nepheline syenites and allied rocks*

* Complex of the Pilandsberg: L^1, Leeuwfontein [320]; L^2, Leeuwkraal [396]; L^3, Losperfontein [119]; F, Franspoort [426]; W, Walmansdal [116]; R, Rietfontein [451

Bushveld complex, the volcanic series, and the sandstone series, of which the contradictory facts already were enumerated by Molengraaff,[1] has not been solved in this way.

As far as concerns this mutual relation, the following facts can be considered as certain:

1. The deep-seated rocks are intrusive in the volcanic series.

2. Dikes which are genetically connected with the deep-seated rocks (felsophyres with the red granites, tinguaites with the nepheline syenites) cut through the sandstone series.

3. The volcanic series show the characteristics of effusive rocks and include sediments (shales and sandstones) in the higher horizons.

4. Sometimes more, sometimes less, clearly the sandstone series rest unconformably upon the volcanic series, the transition being characterized by the existence of conglomerates.

5. In the basal conglomerate of the sandstone series felsitic pebbles sometimes occur.

6. Fragments of a conglomerate, which very closely resembles the basal one, are found in the phonolites of the Pienaars River valley.

When we try to make these facts agree with each other, we meet with great difficulties. It seems to be certain that an effusive period has preceded the main intrusion and that both are connected genetically.

But when we admit, for instance, that the sandstone series are older than the effusive and intrusive series, then the occurrence of felsitic pebbles in the basal conglomerate and the more or less distinct unconformity with regard to the felsites, and also the effusive character of the latter ones and their alternation with sediments, are inexplicable. When we admit that the sandstone series are younger than the effusive and intrusive period, then the intersecting dikes, which are the equivalents of the deep-seated rocks, and also the intrusions of red granite in the sandstone series are unexplained.

We could explain the facts in a rather satisfactory way if we admitted effusion and several intrusions from a deeper-seated

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 59.

mother-magma and considered the Waterberg sandstone as younger than the effusive, but older than the main intrusive, period; then, however, there is no genetic connection between effusion and intrusion.

With H. Kynaston and E. T. Mellor,[1] we can admit a prolonged activity of the Bushveld magma, while the sandstone series were deposited between the main intrusive and effusive period and the later intrusions.

That the nepheline syenites are younger than both the norites and the granites will be proved in the following pages. Only detailed geological and petrographical investigations can clear the true succession from the remnants left after the advanced denudation.

In any case, the following reasons make it undesirable to unite the volcanic series and the sandstone in the Waterberg system.

Over large surfaces at the base of the sandstone series we find developed a basal conglomerate, which rests unconformably, not only upon the felsites, but also upon the red granites; and in the Zoutpansbergen we also find them resting upon much older formations, such as the old granites. Thus it forms a geological horizon over the whole of Central Transvaal and marks an extensive unconformity.

As a rule the pebbles of felsites are rare in this conglomerate, although the relative quantity may increase locally and the unconformity be locally less well developed. In the Waterberg district[2] the conglomerate is principally composed of pebbles of jasper, quartzite with magnetite, white quartzite, schistose quartzite with muscovite, quartz, chert, and felsophyre, which, except the felsophyre, belong to the Swaziland system (Barberton series). Consequently this unconformity must be maintained as a horizon of separation, and the volcanic series must be separated from the sandstone series of the Waterberg system and can either be included in the igneous complex of the Bushveld or else considered as a

[1] H. Kynaston and E. T. Mellor, *The Geology of the Waterberg Tin Fields. Memoir No. 4, Geological Survey of the Transvaal*, Pretoria, 1909.

[2] G. A. F. Molengraaff, "Geologische Aufnahme der Süd-Afrikanischen Republik," *Jahresbericht über das Jahr 1898*, Pretoria, 1900.

separate volcanic series, which is younger than the Transvaal system and older than the Waterberg system and the main laccolithic intrusion.

ACCOMPANYING DIKES AND INTRUSIVE SHEETS

Except the basic rocks, which alternate with the shales and quartzites of the Pretoria series and which are perhaps genetically connected with the intrusion, numerous syenite dikes cut through the Pretoria series and the Dolomite series, and intrusive sheets of red and grey syenite are found in the dolomites. The well-known dike of porphyritic nepheline syenite of the station Wonderfontein in the Potchefstroom district can be followed over Breedts Nek in the Magaliesbergen as far as the nepheline syenites of the Pilandsberg.

At the contact of the intrusive sheets, which have a thickness of three to forty meters, the syenite is finer-grained to microcrystalline, and the dark dolomite has been changed into white marble.

TECTONIC CHANGES CONNECTED WITH THE INTRUSION

The study of the Transvaal system in the neighborhood of the laccolith proves that there are numerous dislocations directly connected with the intrusion.[1]

The strata sank under the weight of the intrusive mass; this explains the increasing of the dip, when the distance from the complex decreases, and also explains why the complex is surrounded by a ridge of harder sediments, which dip toward the central part. In the neighborhood of Pretoria and from there to the west, as far as Rustenburg, we see the ridge of the Magaliesberg quartzites uninterrupted, the strata dipping toward the intrusive complex.

To the east of Pretoria is a series of step faults, which can be followed easily in parallel ridges, which consist of quartzites of the Pretoria series.

We see the dislocations in a remarkable manner where the periphery of the complex forms a re-entering angle as, for instance, at Franspoort east of Pretoria. The ridge of the Magaliesberg

[1] This question was discussed in detail by Molengraaff; cf. *Geology of the Transvaal* (Johannesburg, 1904), p. 50.

quartzites and the accompanying Daspoort and Timeball quartzites here suddenly bend to the southeast. The dip of the strata continues toward the red granites, but the outer ridge of the Magaliesberg quartzites has been fractured and extended in length; the ridge is broken by "poorten." The inner ridges (Daspoort and Timeball Hill quartzites) were strongly pressed in a direction slightly oblique to the strike of the strata. All this is clearly shown by the grouping of the quartzite hills in the neighborhood of Pretoria. That the intrusion and dislocations are directly connected is also evident from the study of the zones of contact in the surrounding sediments in disturbed and undisturbed regions.

CONTACT METAMORPHISM

The quartzites, clay-slates, and "greywackes" of the Transvaal system are strongly metamorphosed by the intrusion of the laccolith. The contact phenomena in connection with the laccolith were first mentioned by Molengraaff and later studied in detail by Hall.[1] The quartzites of the Magaliesberg Range are recrystallized and consist of more or less hexagonal quartz crystals, which sometimes attain a diameter of more than one centimeter; in the clay slates cordierite, andalusite, and biotite appear. The metamorphism decreases when the distance to the laccolith increases, but even the rocks of the dolomite series are metamorphosed. Where the Transvaal system is much disturbed and has undoubtedly been exposed to high pressure, the metamorphosed rocks show a different character in their structure, as well as in their mineralogical composition. These rocks are connected by transitions with the pure contact-rocks of the undisturbed regions.

Muscovite, glaucophane, and zoisite, which are characteristic for the dynamometamorphic crystalline schists, and in small quantities the contact minerals, cordierite, andalusite, and tourmaline, occur in the metamorphosed rocks. Hall decides upon the contemporaneous action of contact and dynamometamorphism in the disturbed regions, from which it is once more evident that the intrusion was directly connected with the dislocations.

[1] A. L. Hall, "Über die Kontaktmetamorphose an dem Transvaalsystem im östlichen und zentralen Transvaal," *Tschermaks Min. u. Petr. Mitt.*, Bd. XXVIII, Heft 1–2 (1909), pp. 115–52.

ROCK TYPES OF THE BUSHVELD COMPLEX

1. *Red granites.*—The acid rocks of the laccolith are amphibole-biotite granites, which are very poor in dark constituents. Principally they show typical granophyric structure. They differ petrographically from the old granites, in essential features enumerated by Molengraaff.[1] In the red granites muscovite is entirely wanting.

2. *Norites, gabbros, and pyroxenites* (*with segregations of iron ore*).—Nearly everywhere at the periphery of the red granites we find a zone of basic and ultra-basic rocks. The basic rocks are found near the western and southern part of the Pilandsberg; they accompany the Magaliesberg quartzites in a south-southeasterly direction to the environs of Rustenburg, where they bend to the east in the direction of Pretoria. The Zwartkoppies and Pyramids have been given their respective names from the color and the form of the small hills, which are composed of these rocks. Finally, they are found from the environs of Belfast to those of Piet Potgietersrust; still farther to the north they are in contact with the old granites. Iron ore has been segregated from these basic rocks at several places; lenticular masses of magnetite are developed nearly everywhere around the Bushveld. At some places these masses are thicker than one hundred meters. The iron ore is magnetite, sometimes with chromite. In the norites the percentage of magnetite goes on increasing, as one approaches the pure magnetite. Ultra-basic pyroxenites and peridotites fill the shallow basin to the West of the Pilandsberg, bounded on the south by the Schurveberg and the Zeerust Hills, on the west by the Marico Hills, and on the north by the Dwarsberg.

3. *Nepheline syenites and syenites.*—These rocks, of which the mode of occurrence and the composition are more fully described in the following pages, are uncovered at several places, often near the boundary of norites and granites.

PNEUMATOLYSIS

As a result of the cooling down and contraction of the intrusive complex and the pressure upon the surrounding strata, numerous

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 44.

fissures were formed, in which different minerals crystallized from the circulating emanations of the magma. The numerous occurrences of tin ore are genetically connected with the red granites of the Bushveld. The copper and silver ores of the Albert mine and the cobalt ores of Balmoral are found in red granite. Finally, we find numerous ore deposits in the Pretoria series, the origin of which is probably directly connected with the intrusion of the Bushveld complex.[1]

THE OCCURRENCES OF ALKALI ROCKS

Common to the occurrences of alkali rocks is the abundance of nepheline syenites. They are exposed at the following places:

1. In the Pilandsberg (Rustenburg district), where they are accompanied by syenites, effusive rocks, and dike rocks.
2. At the boundary of the farms Leeuwfontein [320] and Zeekoegat [287], northeast of Pretoria, where they are accompanied by syenites, leeuwfonteinites, effusive rocks, and dike rocks.
3. On the farms Rietfontein [451] and Spitskop [463], west of Lijdenburg.
4. On the farm Franspoort [426], south of Leeuwfontein [320] (Pretoria district).
5. On the farm Walmansdal [116], northwest of Leeuwfontein [320].
6. On the farm Leeuwkraal [396], still farther to the northwest.
7. On the farm Losperfontein [119] (Rustenburg district).
8. Numerous dikes can be followed from the Pilandsberg in a northwesterly and a southerly to southeasterly direction.

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (1904), p. 52; A. L. Hall, "Geological Notes on the Bushveld Tin Fields, etc.," *Trans. Geol. Soc. South Africa*, VII (1905), 47–55; F. H. Hatch and G. S. Corstorphine, *Geology of South Africa* (London, 1909), p. 216; E. T. Mellor, "Field Relations of the Transvaal Cobalt Lodes," *Trans. Geol. Soc. South Africa*, X (1907), 36; H. Kynaston, "Anniversary Address of the President of the Geological Society of South Africa for 1908," *Trans. Geol. Soc. South Africa*, XII (1909); H. Recknagel, "On Some Mineral Deposits in the Rooiberg District," *Trans. Geol. Soc. South Africa*, XI (1908), 83; "On the Origin of the South-African Tin Deposits," *Trans. Geol. Soc. South Africa*, XII (1909), 168; H. Merensky, "The Rocks Belonging to the Area of the Bushveld Granite Complex in Which Tin May Be Expected, etc.," *Trans. Geol. Soc. South Africa*, XI (1908), 25; H. Kynaston and E. T. Mellor, "The Geology of the Waterberg Tin Fields," *Memoir No. 4, Geological Survey of the Transvaal*, Pretoria, 1909.

THE PILANDSBERG

Where the ridge of the Magaliesberg quartzites—the direction of which was southeast and northwest, to the north of Rustenburg—bends again to the west, a mountain group arises from the rolling

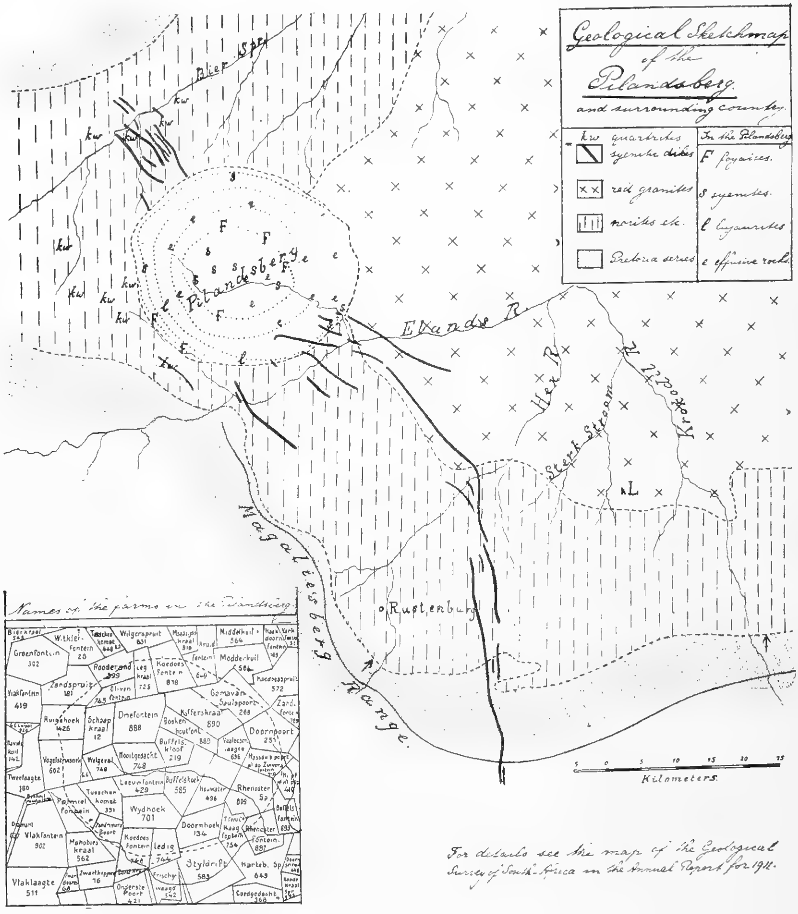


FIG. 2.—Geological sketch map of the Pilandsberg

and undulating country of norites and granites. It has an almost circular outline with a diameter of 15 miles from north to south and 18 miles from east to west. Long ridges and isolated mountains are separated by broad valleys, in which small rivers, dried up in winter, have cut deep valleys with vertical walls.

The first explorer who mentioned the composition of the Pilandsberg and the surrounding region was Adolf Hübner, in his description of a voyage from Potchefstroom to Inyati.[1] Evidently he had observed the peculiar character of these rocks, because he writes: "Am meisten Beachtung verdient wohl das unten zu beschreibende Gestein der Pilandsberge, welches entschieden als ein basisches plutonisches Gestein zu den Grünsteinen gerechnet werden muss." He crossed the Magaliesberg Range along the Hex River at Olifants Nek and traveled from there to Morgenzon [427] (the same direction which the road from Rustenburg to the Pilandsberg still follows); as the rock of the plain of Rustenburg he mentions a typical medium-grained greenstone, which near the contact with the rocks of the Magaliesberg Range crops out in thick sheets.[2] Then he crossed the Elands River and reached the Pilandsberg, which, he says, consists of mountains of greenstones from about 400 to 600 feet high. The meaning of his sentence, "Die Gesammtheit der Quarze bildet ein wahres Massengebirge," is not very clear. He mentions that a part of the mountains consists of a rock which seems to be a "hornblende porphyry," but which shows a syenitic character on closer examination. Because it consists of two minerals, a red "felsite" and a black amphibole, Hübner says that it is not a normal porphyry, though the red feldspar (orthoclase) predominates. The amphibole does not form crystals, but shows rather regular forms. As an interesting feature of this perhaps quite new rock, he mentions the numerous inclusions of clay slate and granite, which do not show any contact metamorphism. According to Hübner, this rock would cover a large area in the Pilandsberg. At several places, e.g., behind the negro town on Saulspoort [369] in the northeastern part of the mountains, granites and eruptive breccias, which contain fragments of porphyrite and granite, occur. Because Hübner mentions that he visited the missionary station on Saulspoort, he perhaps speaks about these rocks, which occur in the neighborhood of syenites with red feldspars.

[1] Adolf Hübner, "Geognostische Reisen in Süd-Africa," *Peterm. Geogr. Mitt.*, XVIII (1872), 424, 426.

[2] These rocks probably are the norites with schistose structure in the margin of the igneous complex of the Bushveld.

Nearly at the same time as Hübner, Carl Mauch[1] made geognostical studies in the central part of South Africa. In a chapter, "Mein erstes Jahr in der Transvaal Republik," he describes his "Irrfahrten in den Pilaans-Bergen." Coming from Rustenburg, he passed a conical hill and entered the central part of the mountain complex and found "quartz porphyries" with a violet-brown groundmass in the bed of a rivulet. After nearly perishing with hunger and thirst, he was received hospitably in the house of the missionary, who still lives in the native *stadt* on Saulspoort. From the western part of the mountains he mentions pieces of copper ore, magnetite, fluorine, and pebbles of gneiss. Most probably his quartz porphyries are the rocks without quartz, with porphyritic feldspars in a reddish, dense or fine-grained groundmass, which are the effusive equivalents of the syenites and nepheline syenites of this region. His gneiss probably is the schistose lujaurite which covers large areas in the western and southern part of the mountains.

In his sketch of the South-African Republic, G. A. F. Molengraaff[2] gives a review of the knowledge about the rocks of the Bushveld, and here the results of Mauch and Hübner are mentioned.

In 1898 J. A. L. Henderson[3] described a syenitic rock from the Pilandsberg as pilandite. The true character of the rocks of the Pilandsberg was recognized by Molengraaff[4] in 1904. In a short geological description of the Pilandsberg and a part of the Rustenburg district he mentions that different varieties of foyaites are of widespread occurrence and the schistose varieties, which are very rich in aegerine, are compared with the lujaurites of Greenland. The rock specimens, which Molengraaff collected, were studied by me, and the results of this study were published in the petro-

[1] Carl Mauch's "Reisen im Innern von Süd-Afrika, 1865–1872," Ergänzungs-Bd. VIII (1873–74), *Peterm. Geogr. Mitt. No. 37.*

[2] G. A. F. Molengraaff, "Schets van de Bodemgesteldheid van de Zuid-Afrikaansche Republiek," *Tijdschr. Kon. Aardr. Gen.* (Leiden, 1890), p. 604.

[3] J. A. L. Henderson, *On Certain Transvaal Norites, Gabbros, Pyroxenites and Other South-African Rocks.* London, 1898. Dulau and Co.

[4] G. A. F. Molengraaff, "Preliminary Note on the Geology of the Pilandsberg and a Portion of the Rustenburg District," *Trans. Geol. Soc. South Africa,* VIII (1905), 108.

graphical part of my first paper. In the winter of 1910 I visited the occurrences of nepheline syenite in the Transvaal, especially that of the Pilandsberg (during the last two weeks of June).

After this visit I was able to give a brief description of the general geology of the neighborhood.[1] I showed that these mountains consist of red syenites, nepheline syenites, and their porphyritic and dense equivalents, and, with a sketch map, that the main rock types are disposed in concentric circles. As far as concerns the red syenites, I was able to show that they often are covered by the effusive rocks, while they probably were older than the nepheline syenites of the complex. There was clear evidence that the rocks of the Pilandsberg intrusion are younger than the granites and norites of the igneous complex of the Bushveld; dikes, which are genetically connected with the intrusion, cut through the granites and norites. The intrusion of nepheline syenites on Leeuwfontein [320] was shown to be certainly younger than the Waterberg system, because a dike of tinguaite, which has the same chemical composition as the normal foyaites of Leeuwfontein, cuts through Waterberg sandstones and conglomerates on Paardefontein [338].

The mapping of the Pilandsberg and surrounding area was carried out in the next year by Dr. Humphrey, in company with Dr. P. Wagner, in connection with the work of the Geological Survey of South Africa.[2] Humphrey divides the whole of the rocks into two main groups: the nepheline syenites and phonolites; and the alkali syenites and trachytes. Each of these groups contains a plutonic and an effusive representative and "the reason for this classification is that the rocks forming the Pilandsberg are the denuded remnants of what was once a stupendous volcano, comparable in size with the greatest of the present-day active volcanoes."

General character of rocks.—The foyaites and other allied rocks in Professor Molengraaff's collection have been described by me

[1] H. A. Brouwer, *Oorsprong en samenstelling der Transvaalsche Nepheliensyenieten* (1910), pp. 12–29.

[2] W. A. Humphrey, "The Volcanic Rocks of the Pilandsberg," *Trans. Geol. Soc. of South Africa*, August 19, 1912; "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 77.

in detail. Because the study of the alkali syenites and effusive rocks which were collected during my visit in 1910 has been postponed by my departure for the East Indies, we will mention the most characteristic features of the latter rocks, as they have been briefly described by Humphrey.

The richness in pneumatolytic and thermal minerals (especially fluorspar) is characteristic for the rocks of the whole region; accordingly the loss on ignition is always considerable.

Besides the coarse- to medium-grained intrusive rocks and the effusive ones, transitional types have a great development. A series of porphyrites which graduate through all the types between true lavas, intrusive sheets, and dikes often form an unbroken series paralleling the effusive rocks.

Nepheline syenites: The nepheline syenites partly belong to the group of the foyaites and are usually coarse-grained. They are connected by transitions with the lujaurites, which are characterized by the abundance of small needle-shaped crystals of aegirine and are quite similar to the lujaurites of Greenland and the peninsula of Kola. The latter rocks principally are found in the southern part of the mountains, while lujauritic rocks only exceptionally occur in the central part. The foyaites have been frequently found by Humphrey in dikes, traversing the various effusive rocks and the red syenites.

If we divide the foyaites according to the character of the dark minerals, we find that nearly all the subgroups are represented and, in the porphyritic varieties, we also find aegirine, alkaline amphiboles, and biotite, either characterizing different rock types or occurring together in the same rock. The amphiboles are rich in alkalies and often show peculiar properties which are similar to those often mentioned in the literature of the foyaitic and theralitic rocks. Their optical and chemical properties have not yet been studied in detail, but they are known to have the properties of the barkevikitic, kataforitic, or arfvedsonitic amphiboles.

The isolated range of hills to the southeast of the Pilandsberg proper, which bends around with the lujaurites, consists of aegirine-amphibole foyaites, in which the amphibole has a pronounced zonal structure. The differences in color are progressive from brown

in the central part to green in the margin, while a turning of the plane of optic axes from parallel to the plane of symmetry in the central part to normal to it in the margin was often observed. The extinction angles in sections parallel to [010] are up to 40°. Amphiboles in which the plane of optic axes is normal to the plane of symmetry have also been found in pegmatitic segregations in aegirine-amphibole foyaites on Buffelspan [585]. Their angle of optic axes is very small and the extinction angle **b**:*c* is about 14°. In rocks from Wijdhoek [701] many properties of the amphiboles agree with those of the green amphiboles which Ussing[1] described in rocks from Greenland.

Coarse-grained foyaites are largely developed in the central, and also in the northern, part of the mountains. The hills and a part of the valley on and near Boekenhoutfontein [889] consist of foyaites, which contain aegirine and sometimes are very rich in biotite; more to the south, at Buffelspan [585], coarse-grained aegirine-amphibole foyaites are found. Rocks with the same structure occur in the western part of Houwater [496] and gray foyaites cover a large surface on Schaapkraal [12]. Leucocratic foyaites with aegirine as the only dark constituent are found in the western part of Wijdhoek [701], near the eastern boundary of Tusschenkomst [331]; they are associated with aegirine-amphibole foyaites. They form a complex of isolated small hills in a valley, surrounded by ridges of effusive rocks. The foyaites can be followed to the southern part of Leeuwfontein [429] and to Welgeval [749]. At Wijdhoek [701] they show a considerable amount of variation in structure and composition; we find gray feldspar rocks, which contain biotite as the only dark constituent, varieties which are rich in nepheline, and porphyritic equivalents in which the dark minerals appear as phenocrysts enclosing the elements of the fine-grained groundmass.

The lujaurites are characterized by their richness in fine needles of aegirine. In a forthcoming petrographical paper this group will be described in detail. Aegirine always predominates; arfved-

[1] N. V. Ussing, "Mineralogisk-petrografiske Undersögelser of Grönlandske Nefelinsyeniter og beslaegtede Bjaergarter," *Meddelelser om Grönland*, XIV (1894), 210.

sonite is a rare constituent of the rocks from the Pilandsberg, while true arfvedsonite lujaurites have been described by Ussing from Greenland. The lujaurites are connected with the foyaites by rock types poorer in dark minerals, aegirine with the needle form gradually disappearing. Like the lujaurites from other regions (Greenland, Kola peninsula, and Los islands), the rocks of the Transvaal are characterized by an abundance of rare minerals. For example, the new mineral molengraaffite,[1] of the eucolite group, which sometimes occurs in the foyaites, is very common in these lujaurites.

At both sides of the Rustenburg road, on Ledig [744], we find tinguaitic rocks and porphyritic lujaurites between the high lujaurite hills and the norites; to the east the lujaurites can be followed to Doornhoek [134]. Their southern parts are covered by effusive rocks. To the northwest, bending round with the periphery of the Pilandsberg, we can follow the lujaurites to the southwestern part of Wijdhoek [701]; farther to the northwest the periphery of the complex is formed by red to light-red syenitic rocks. On Tusschenkomst [331] we find the same lujaurites in contact with the effusive rocks, where a valley separates ridges of the two rocks.

The tops of the eroded lujaurite ridges are similar to those of inclined crystalline schists.

We find the lujaurites and their porphyritic equivalents also in the western, northern, and northeastern part of the complex, beside the red syenites; in the eastern part, where the effusive rocks have their greatest development, the latter rocks cover the whole surface from the periphery to the central foyaites. Probably the lujaurites occur there at greater depth. The nepheline syenites and the allied rocks which hitherto have been studied microscopically belong to the following groups:

1. Aegirine foyaites
   Leucocratic rocks
   Mesocratic rocks
   Foyaitic lujaurites

[1] H. A. Brouwer, "Molengraaffit, ein neues Mineral in Lujauriten aus Transvaal," *Centralbl. f. Min., etc.*, 1911, p. 129.

2. Lujaurites
   a) Eucolite-molengraaffite lujaurites
   b) Eucolite lujaurites
   c) Eucolite-astrophyllite lujaurites
   d) Aenigmatite lujaurites
   e) Lujaurites without eucolite
3. Aegirine-amphibole foyaites
4. Aegirine-biotite foyaites
5. Lujaurite porphyries
6. Aegirine-nepheline syenite porphyries without foyaitic structure
7. Aegirine-amphibole-biotite-nepheline syenite porphyries
8. Tinguaite porphyries

Syenites: The syenites generally have a red or reddish color; they principally consist of feldspar, while the dark-colored minerals have usually been altered into chlorite. Iron ores, titanite, apatite, and fluorspar are further constituents of these rocks.

Humphrey[1] mentions that the red syenites of the eastern, western, and central parts of the Pilandsberg have various points of dissimilarity in the hand specimens; those of the east, on Rhenosterspruit, being almost entirely composed of feldspar, while the other localities furnish rocks in which is much iron ore. The latter rocks are very decomposed. The feldspars are microcline, orthoclase, and anorthoclase. Two analyses of red syenites, which have been published in the *Annual Report of the Geological Survey of South Africa* for 1911, show that there are considerable differences in chemical composition between the rocks of this group. A red syenite from Nooitgedacht [748] contains 8 per cent Na_2O and 2 per cent K_2O, while a red syenite from Rhenosterspruit [609] contains 5 per cent Na_2O and 10 per cent K_2O. The high potash content of some of the syenites tends to connect them with the leucite-bearing effusive rocks, which will be mentioned below.

These red syenites bound the Pilandsberg complex on the northwestern, northern, and southeastern sides. For the greater part they are developed as a massive wall, forming the outermost circle of hills at the periphery of the mountains. The red color of the syenites has given the name to the farm Rooderand [399] and from

[1] W. A. Humphrey, "The Volcanic Rocks, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 104.

there to Saulspoort [369] the syenites form the periphery of the complex; to the south, along Ruigehoek [326], Vogelstruisnek [602], and Palmietfontein [567], they form a nearly interrupted series of bare, low hills. In the southern part, near the road from Rustenburg to Saulspoort [269], steep lujaurite hills rise from the flat norite country. In the southeastern part, where the Rhenosterspruit leaves the hills, we again see the bare, red syenite hills on both sides of the stream. Along the eastern boundary they are covered by effusive rocks. The syenites are found also in the central parts of the complex; in the southern part of Driefontein [888] numerous hills consist of these rocks. They form a conspicuous feature and from a distance can easily be distinguished from the rounded, bare, felsite ridges. We find them also in the southeastern part of Welgeval [749], on Nooitgedacht [748], Buffelskloof [219], Leeuwfontein [429], Buffelspan [585], and Houwater [496]. Near the houses on Nooitgedacht [748], in the valley of a small rivulet, light syenitic rocks with white feldspars occur, which are similar to some varieties of the rocks on Leeuwfontein [320] in the Pretoria district.

By transitions these rocks are connected with the nepheline syenites, as well as with the effusive rocks.

Diorites: As intimately associated with the foyaites and lujaurites, Humphrey[1] mentions the occurrence of diorites, which have their greatest development in the northern part of Boekenhoutfontein [889]. They are also exposed on the summit of the mountain to the southwest of the native *stadt* on Saulspoort and are found as a dike cutting through the norites on Tusschenkomst [446] to the north-northwest of the Pilandsberg complex. The rock is fine grained, has a gray color, and consists principally of augite and labradorite.

Effusive rocks: In my previous paper[2] it has been stated that porphyritic and dense equivalents of the syenites and nepheline syenites have a great development in the Pilandsberg complex. Flow structure is often beautifully developed in these rocks.

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 84.

[2] *Oorsprong en samenstelling der Transvaalsche Nepheliensyenieten*, p. 16.

The effusive rocks have recently been described in some detail by Humphrey in a paper on the volcanic rocks of the Pilandsberg.[1] He divides the rocks into two main groups—the trachytes and the phonolites. The first group contains the effusive representatives of the alkali syenites; the second group, those of the nepheline syenites. An andesitic rock was found on the ridge separating the farm Kafferskraal [890] from Saulspoort [269]. It consists of diallage, diopside, plagioclase, and iron ore in a fine-grained groundmass, and may be an effusive representative of the diorites. The rock has been classed as leucitophyre. The phenocrysts of orthoclase are accompanied by phenocrysts of leucite.

The trachytes attain their greatest development in the eastern portion of the Pilandsberg, on the farms Doornpoort [251] and Vaalboschlaagte [636], where they measure some 5,000 feet in thickness. In this succession the trachytes alternate with red "felsitic"[2] rocks and tuffs, while a thick band of leucitophyres occurs toward the base of the series. These blue-colored leucite-bearing rocks contain phenocrysts of orthoclase and leucite in a groundmass of very finely divided aegirine and feldspar. The phonolites occur in most other parts of the Pilandsberg; they are of a prevailing greenish and bluish color, contrary to the prevailing red of the trachytic series. Typical phonolites on the farm Driefontein [888] contain occasional phenocrysts of feldspar in a finely divided groundmass which consists of feldspar, nepheline, and much aegirine. In the neighborhood of Saulspoort is a rock containing phenocrysts of sodalite in a cryptocrystalline groundmass.

Volcanic breccias and tuffs are widely distributed throughout the Pilandsberg.

The effusive rocks of the isolated mountain at the boundary of Buffelspan [585], Leeuwfontein [429], and Wijdhoek [701] often have a banded appearance, and a beautiful flow structure with parallel arrangement of the feldspar phenocrysts is developed. Well-developed cubes of blue fluorine occur in some of these rocks, while Humphrey mentions the occurrence of leucite crystals. He

[1] "The Volcanic Rocks, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 105.

[2] Felsite is a field term under which Transvaal geologists comprise a great diversity of rocks: quartz porphyries, felsites, phonolites, tinguaites, andesites, etc.

found the effusives to form a thick capping resting upon the red syenites. The effusive rocks are found in the northeastern part of Buffelspan [585], in the high ridge from Houwater [496] to Wijdhoek [701], and appearing again at the other side of the Rustenburg road, where the effusives of the ridge are in contact with lujauritic rocks and can be followed in a northwesterly direction. On Tusschenkomst [331] and Welgeval [749] they are separated from the lujaurite by a shallow valley at the contact. Still more to the north we find the effusive rocks on Schaapkraal [12] and on Driefontein [888], where they are exposed in the valley of a rivulet, which flows in the direction of Rooderand [399]. On the northern farms of the Pilandsberg the high ridges of effusive rocks bend around parallel to the circumference of the complex; on the western farms they have their greatest development and almost entirely hide the deep-seated rocks.

The rocks of the country around the Pilandsberg.—The rocks which surround the Pilandsberg complex are the norites and granites of the Bushveld igneous complex and the quartzites and shales of the Pretoria series.

Norites and Pyroxenites: These rocks form the characteristic small hills (Pyramids, Zwartkoppies) parallel to the Magaliesberg range. They bend to the northwest in the neighborhood of Rustenburg, but the characteristic hills disappear long before they reach the Pilandsberg; much more to the north, on the farm Modderkuil [565], we see them again just in the continuation of those to the south of the Pilandsberg. The bands of magnetite are found to the southeast of the Pilandsberg. They end against the red syenites near the boundary of the farms Rhenosterfontein [867] and Rhenosterspruit [906], but are found again to the north of the Pilandsberg. We see that the whole southern part of the Pilandsberg is immediately surrounded by the basic rocks; on the farms Ledig [744] and Koedoesfontein [818] they are in immediate contact with lujaurites and allied rocks. Near the boundary of Zandrivierspoort [747] and Mahobieskraal [562] the isolated hills of aegirine-amphibole foyaites and the ridges of Magaliesberg quartzite come close together. At a small distance farther to the northwest and to the west the basic margin of the Bushveld com-

plex is again largely developed. It covered the whole region, which is limited to the south by the Schurvebergen and Zeerust Hills, to the west by the Marico Hills, and to the north by the Dwarsbergen.[1]

In following the basic margin along the western boundary of the Pilandsberg, we find quartzites in the northern part of Vogelstruisnek [602] which are in immediate contact with red syenites. More to the north the latter rocks border again upon norites. Near, and west of, the native *stadt* on Ruigehoek [426] norites rich in feldspars are exposed in the valley of a rivulet; they are the same rocks as those which are found to the south of the Pilandsberg, but show a pronounced schistose structure and a dip to the northeast. To the west the rocks become more basic, and near the contact with the quartzites on Davidskuil [142] very basic rocks were collected in the valley of a rivulet which is crossed by the road from the native *stadt* on Mabieskraal [620] to Janskop on Bierkraal [545]. They, too, show a pronounced schistose structure. Here the strike is about N. 15 W., and the dip is to the east-northeast.

On Tusschenkomst [446], to the east of the quartzite hill Janskop on Bierkraal [545], a series of hills consisting of schistose basic rocks can be followed in a north-northwesterly direction. Humphrey[2] mentions a peculiar feature of the pyroxenites, particularly noticeable on the farms Ruigehoek [426] and Zandspruit [181], where narrow bands of chromite, dipping to the east, have formed a band of comparatively high ground and an apparent stratification.

From all that has been said above, it is evident that the basic margin of the plutonic complex *is cut off abruptly* by the intrusion of the Pilandsberg.

Granites: The red granites of the igneous complex of the Bushveld are found to the east of the norites. The boundary between the two rock types crosses the Elands River in the southeastern part of Rhenosterfontein [867] and ends against the alkali syenites. The red granites are found all along the eastern part of the Pilandsberg; on Saulspoort [269], west of the Rustenburg road, the

[1] F. H. Hatch, *Trans. Geol. Soc. South Africa*, VII (1904), p. 1.

[2] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 81:

boundary between the norites and granites begins against the effusive rocks of the Pilandsberg complex and runs from there in a northeasterly direction. The occurrence of brecciated rocks with granite boulders in the hill behind the Saulspoort Mission station, which was already mentioned in my previous paper, has been studied in detail by Humphrey,[1] who found various types of igneous rocks. The relationship between these is very complicated. Syenite is seen to be intrusive into the effusive rocks and fragments of granite are found within the syenites and effusive rocks. Farther up the hill there is an extensive outcrop of granite which extends for some 800 yards along the face of the hill. Above this granite is found a diorite, and the crest of the hill is formed by effusive rocks. Breccias, in which granite occurs as included boulders, and also repeated outcrops of granite were found on Doornpoort [251] and Zuiverfontein [718] in the eastern marginal part of the Pilandsberg. Large boulders of red granite embedded in coarse red syenite are to be seen in the bed of the Rhenosterspruit on the farm Rhenosterspruit [609].

Pretoria series: The Magaliesberg Range, which from Rustenburg strikes in a northeasterly direction, comes to an abrupt end on Mahobieskraal [567], to the southeast of the Pilandsberg complex. Then the Pretoria beds bend to the west; near Bechuanaland they have a short northerly direction, and then return again to the east, passing at a distance of about 8 miles to the north of the Pilandsberg complex and forming the northern boundary of the igneous complex of the Bushveld.

Isolated hills of quartzite are found at several places to the east of the Pilandsberg. On Vogelstruisnek [602] they are in immediate contact with the red syenites. Other hills of quartzite occur on Tweelaagte [180], Vlakfontein [902], behind the native *stadt* on Mabieskraal [620], on Davidskuil [142], and still more to the north on Bierkraal [545]. From Janskop on Bierkraal the quartzite hills extend still more to the east, where they approach the northern boundary of the igneous complex of the Bushveld.

Between the Pilandsberg and the Marico River, the Upper Magaliesberg beds are missing from the normal sequence of the Pretoria series. They are represented by the isolated hills of

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 87.

quartzite, which are entirely surrounded by rocks belonging to the igneous complex of the Bushveld and most probably were broken up in connection with the intrusion of this complex.

Dike rocks.—The first nepheline syenite of the Transvaal was discovered by Elie Cohen[1] in 1872, near the Hex River, between Renseburg and Rustenburg. He states that this rock forms the lower parts of the Zwartkoppies, where these hills bend to the northwest. The rocks collected by Cohen were described by E. A. Wülfing[2] in 1886 as porphyritic foyaites in which the nepheline only occurs in the groundmass.

In 1904 G. A. F. Molengraaff[3] collected nepheline syenites on the farms Elandsheuvel [255] and Tweede Poort [189]; these rocks are porphyritic foyaites in which nepheline occurs as phenocrysts. These rocks are described in the petrographical part of my previous paper. Since that time the sheet Rustenburg (sheet No. 4) has been mapped by the Geological Survey of the Transvaal, and it is shown that several dikes of these porphyritic foyaites intersect the rocks of the Bushveld complex, running from the Pilandsberg in a southeasterly direction.

Some of them even cut through the Magaliesberg Range to the east of Rustenburg and can be followed still farther to the south.

A fine-grained red syenitic rock was found by me to the north of the red hill on Rooderand [399], cutting through the norites in a nearly northerly direction. At the boundary of Groenfontein [302] and Bierkraal [545] near the quartzites, a porphyritic syenite was found in the basic rocks. On Plate XIV in the annual report for 1911 of the Geological Survey of South Africa it is shown that several syenitic dike rocks can be followed from the Pilandsberg in a north-northwesterly and northwesterly direction.

All these dikes cut through the norites and granites of the Bushveld, *and they have been intruded after the consolidation of the rocks of the Bushveld igneous complex.*

[1] E. Cohen in *Berichte über die XVI. Versammlung des Oberrheinischen Geologischen Vereins*, am 29 März, 1883, Stuttgart.

[2] E. A. Wülfing, "Untersuchung eines Nephelinsyenits aus dem mittleren Transvaal," *Neues Jahrb. f. Min. Geol. u. Pal.*, 7 Mai, 1888, Bd. II, p. 16.

[3] G. A. F. Molengraaff, "Preliminary Note on the Geology of the Pilandsberg," *Trans. Geol. Soc. South Africa*, VIII (1905), 208.

Inside the Pilandsberg several dikes occur. Some dike rocks with the macroscopic appearance of the tinguaites form a band of comparatively high ground, because of their resistance to denuding agencies. On Boekenhoutfontein [889] near the boundary with Kafferskraal [890] a dike of this kind strikes N. 50 W.; it measures about 10 meters across and cuts through the foyaites with biotite; the contact with the foyaites is formed by a bent line, as well as the contact of a dike in the southeastern part of Koedoesfontein [649].

Near the boundary of Driefontein [889] and Nooitgedacht [148] I found a tinguaitic dike, 2 meters in diameter, with a sharp contact and a northeasterly strike, cutting through medium-grained nepheline syenites in the valley of a rivulet. Near the contact the rock has a glassy appearance; in the central part the structure is porphyritic. This dike dips steeply to the northeast. At the boundary of Olivenfontein [145] and Rooderand [398], in the valley to the south of the red syenites, a similar dike, which measures 5 meters across, is exposed.

The direction of these dikes agrees nearly with that of the dikes outside the Pilandsberg. In the western rivulet to the north of the houses on Driefontein [888], a tinguaitic dike or segregation, averaging 40 centimeters in width, has a blended contact with the surrounding lujaurites. It is rich in bronze-brown flakes of mica. Near the lujaurites the rock is very rich in aegirine; this mineral is often developed in spherulites which are up to 1 centimeter in diameter.

According to Humphrey,[1] dikes of foyaite, red syenite, nepheline syenite, and diorite occur in all parts of the Pilandsberg, and, in addition to these, there are many basaltic and tinguaitic varieties occurring in various parts. In the spruit on Saulspoort [269] a dike of red syenite cuts through the effusive rocks. A series of red "felsitic" dikes and blue-black glassy dikes, which were difficult of determination, and dikes of nepheline syenite traverse the red syenites. The dikes of nepheline syenite, which have their greatest development outside the Pilandsberg, seem to disappear into the

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 85.

nepheline syenites in the central part of the complex. Dikes of foyaite were found traversing the red syenites of the central part.

From all that has been said above, it is evident that *the foyaites are the youngest rocks* of the Pilandsberg complex, while there is good evidence to show that the red syenite is older than some of the effusive rocks.

Pegmatites.—Dikes of pegmatite, which in many other nepheline syenite regions contain numerous rare minerals, were not met with during my visit. Coarse-grained pegmatitic segregations in the normal-grained rocks are of frequent occurrence, but the rare minerals were not found in much larger crystals than in the normal-grained varieties.

Pegmatites rich in eucolite are well exposed in lujauritic rocks from the hills to the north of the houses on Driefontein [888]. They consist principally of large crystals of feldspar, green nepheline, long crystals of aegirine, and carmine-red eucolite which is partly altered to catapleiite; they also contain some astrophyllite. The prisms of aegirine are up to 10 centimeters in length, and sometimes show a graphic intergrowth with feldspar. Near, and to the west of, the main road to Saulspoort [269] where it crosses the Rhenosterspruit in the northeastern part of Buffelspan [585], we found pegmatites in the aegirine-amphibole foyaites. Feldspars up to 10 centimeters in length, green nepheline, prisms of amphibole, and prisms or spherulites of aegirine are the main constituents; they also contain some fluorine. Amphiboles with a very small angle of optic axes *in which the plane of the optic axes is normal to the plane of symmetry*[1] occur in these rocks. In the southern part of Wijdhoek [701], near, and to the west of, the main road and to the south of the ridge of effusive rocks, we found pegmatites, which are very rich in astrophyllite and spherulites of aegirine, measuring up to several centimeters in diameter. They are found still farther to the southwest on Koedoesfontein [746] in a rivulet which joins the Wolvespruit, where numerous blocks of pegmatites and lujaurites could be collected; some of them are very rich in eucolite.

[1] H. A. Brouwer, "On Zonal Amphiboles in Which the Plane of Optic Axes of the Margin Is Normal to That of the Central Part," *Proceed. Kon. Akad. Amsterdam*, XVI (1913), 275.

The aegirine-biotite foyaites in the northwestern part of Boekenhoutfontein [889] contain pegmatitic segregations and small dikes in which feldspars, feldspathoids, and eucolite mineral and small pale-yellow needles occur. Often they are very rich in aegirine; this agrees with its tardy crystallization in most of the rocks of the region.

Finally, we found segregations in the lujaurites to the west of the common boundary post of Tusschenkomst [331], Leeuwfontein [429], and Wijdhoek [701]; they consist almost entirely of aegirine spherulites which are up to some centimeters in diameter.

Segregations rich in fluorine occur in the microfoyaites of Olivenfontein [745], and segregations rich in large aegirine spherulites occur in mesocratic foyaites of the valley, running in a north-south direction in the northeastern part of Buffelspan [585].

Humphrey mentions the occurrence of very coarse-grained pegmatites with much fluorspar on Doornhoek [134] and beautiful pegmatites, about half a mile from the homestead on Driefontein [888] on the main road to Buffelskloof (219).

Mechanism of intrusion of the Pilandsberg complex.—Since the rocks of the Pilandsberg complex are younger than the red granites and norites of the Bushveld igneous complex, and since the Pilandsberg is surrounded on three sides by norites and on one side by red granites, it seems to be beyond doubt that the space which is occupied by the Pilandsberg intrusive rocks was occupied, prior to the intrusion, by the norites and red granites of the Bushveld.

That the removal of the original rocks was not the result of folding is proved by the occurrence of a great number of vertical dikes of vast extension, which are genetically connected with the intrusion.

The hypothesis that the subsidence of crust blocks elsewhere was the cause of the intrusion of the magma and the hypothesis of laccolithic intrusion seem not to be applicable in the present case.

As has been stated by Humphrey, there can be no doubt that the Pilandsberg represents the remnant of what was once an important focus of eruption, and the hypothesis that the intrusive magma has filled up the cavities which were formed by volcanic outbursts of an explosive character seems to be applicable.

Tuffs and volcanic breccias are found all over the areas where the effusive rocks are developed. The main rock types of the Pilandsberg are disposed in concentric circles, of which the outermost consists of syenites and nepheline syenites and is followed toward the center by a ring of effusive rocks. The latter dip, with a few local exceptions, from the center outward, and the highest hills formed by intrusive rocks in the central area of the complex still carry a capping of volcanic rocks which have resisted denudation.

If the Pilandsberg is considered as the remnant of what was once a volcano and its subsidiary peripheral vents, this must have been of stupendous dimensions, since the intrusive rocks cover a surface whose diameter varies from 15 to 18 miles, the lavas having extended far beyond the periphery of the intrusives.

It is peculiar that in the territory of the Pilandsberg effusive rocks are found in large quantity between the granular rocks, whereas they do not occur in the surrounding granites and norites. The lavas, which must have extended far beyond its periphery, have entirely disappeared and do not even cap the hills of Magaliesberg quartzite, though at some places the quartzite is found in the immediate neighborhood of the Pilandsberg. It is very likely that in connection with the intrusion of the alkali rocks the roof has locally sunk down, and, while it has disappeared everywhere else in the neighborhood by erosion, we see the remains preserved just on those spots where the roof has given way.

Subsidences in ancient volcanic regions are by no means rare. Judd,[1] for instance, mentions the comparatively perfect state of preservation exhibited by the great volcano of Mull, if compared with that of the other great Tertiary volcanoes in the Hebrides. It can be shown that this difference is due to a central subsidence which took place in the Mull volcano. From the sections along the shores of the deep fiords it is evident that the basaltic lava sheets dip toward the central mass of eruptive rocks, the inclination increasing as we approach the volcano. Further, there is clear

[1] J. W. Judd, "On the Ancient Volcanoes of the Highlands and the Relations of Their Products to the Mesozoic Strata," *Quart. Journal of the Geol. Soc.*, XXX (1874), 256.

evidence of the existence of faults, the downthrow of which is in all cases toward the great central mass. A similar subsidence took place after the period of the eruption of acid lavas and before that of the basaltic lavas.

The state of preservation of the Pilandsberg complex and surrounding area is not very favorable to a study of the amount of subsidence in the sunken area. The lavas, which must have extended far beyond the mountain proper, have entirely disappeared; the junction of the intrusive rocks of the Pilandsberg with those of the Bushveld is not well exposed; and the amount of denudation in the area surrounding the complex cannot be estimated. This probable subsidence and the large dimensions of the plutonic body lead us to mention another hypothesis to explain the mechanism of intrusion of many batholites, which has been set forth by Daly.[1] He termed this process "overhead stoping"; it consists of a continued breaking free of roof blocks and a sinking down of the detached blocks into the magma, which consequently rises and occupies the place of the sunken fragments.

The cover of the intrusive rocks of the Pilandsberg entirely consists of lavas, the effusive equivalents of the intrusive rocks, and this is very common in batholitic intrusions from other parts of the world. How these facts are explained by overhead stoping has been elaborately discussed by Ussing[2] in a recent treatise on the geology of the country around Julianehaab. If a batholitic magma on one or more occasions during its intrusion has penetrated its cover, this will presumably lead to a volcanic outburst of catastrophic character, accompanied by the outpouring of lava flows and followed by a period of quiescence. After a time, when hot magma from below is brought into contact with the newly formed roof, the stoping process will continue, interrupted by few volcanic outbursts until the magma has cooled to its point of solidification.

In several batholites with a permanent cover of sedimentary rocks the stoping process came to an end and the magma was

[1] R. A. Daly, "Geology of the Ascutney Mountain," *Un. St. Geol. Surv. Bull. No. 209* (1903), p. 93; "The Mechanics of Igneous Intrusion," *Amer. Jour. of Science*, 4th series, XV (1903), and XXVI (1908).

[2] N. V. Ussing, "Geology of the Country around Julianehaab, Greenland," *Medd. om Grönland*, XXXVIII (1911), p. 302.

solidified before the earth's surface was reached, but the Pilandsberg alkali magma must have been very rich in mineralizing agents, which reduced its viscosity, and in such magmas the stoping process may go on when they near the earth surface and until the cover is penetrated. Volcanic outbursts cause an escape of the volatile substances, and the magma becomes more and more viscous, until a new supply of heat and mineralizers from below sets up stoping again. In fact, several rare minerals with a highly complex constitution, which are not stable at high magmatic temperatures, occur within the Pilandsberg rocks. Fluorine is a very common constituent, and, as their very name imports, fluorides must have reduced the viscosity considerably. Moreover, fluorine and other minerals in which we find direct evidence of the co-operation of mineralizers are regularly distributed in several rocks of this region, where they crystallized in the last cavities, thus proving that the mineralizing agents in part were regularly distributed until the final consolidation.

Of course, direct support would be given to the co-operation of overhead stoping if fragments which could only be derived from an original cover of the crystalline rocks were found among the rocks of the Pilandsberg complex, but Humphrey[1] mentions that all the close-grained rocks, which in the hand specimens very much resemble shales, proved themselves under the microscope to be devitrified lavas.[2] Particularly at those places in the northeastern part of the area where the granites are found to within a few hundred yards of the Pilandsberg complex it is of great interest to know whether these granites occur in their original position.[3]

Age of the Pilandsberg.—In the neighborhood of the Pilandsberg the rocks which formed the covering of the igneous complex of the Bushveld at the time of its intrusion most probably belonged to the

[1] "The Volcanic Rocks of the Pilandsberg, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 102.

[2] In my previous paper (*Oosprong en samenstelling der Transvaalsche Nephelien-syenieten*), p. 17, I mentioned having found shales in the valley to the north of the homestead on Houwater [496], but the rocks were not studied under the microscope.

[3] Cf. also H. A. Brouwer, "On the Formation of Primary Parallel Structure in Lujaurites," *Proc. Kon. Akad. Amsterdam*, 1912, p. 734.

Waterberg system; they have here been entirely removed by denudation. Humphrey mentions that there are no signs of the presence of Waterberg rocks among the stratified lavas, nor were any fragments of those rocks found among the volcanic breccias, while many examples of included granite boulders within the Pilandsberg rocks were found.

He concludes that the volcanic outbursts and the outpouring of lava postdated the removal of all of the sedimentaries of the Waterberg system in this neighborhood. No evidence is available about the age of the Pilandsberg rocks with regard to the Karroo system.

Of course, if the possibility of overhead stoping is admitted, the problem of the age of the Pilandsberg rocks is more complicated, but the question of the mechanism of intrusion is still too vague for further discussion.

OTHER OCCURRENCES OF NEPHELINE SYENITES AND ALLIED ROCKS

The occurrence of nepheline syenites on Leeuwfontein [320] and Zeekoegat [287] was discovered by Molengraaff in 1898.[1] The numerous variations of the Leeuwfontein foyaites in chemical and mineralogical composition and also the leucocratic and melanocratic dike rocks, bostonites, monchiquites, tinguaites, etc., were described. Liebenerite porphyries, like those which occur at Predazzo in the Tyrol and at Alnö (Sweden), are also associated with the nepheline syenites of this region.

D. Draper discovered nepheline syenites on Walmansdal [116] to the northwest of Zeekoegat [287]. The rocks to which J. A. L. Henderson[2] gave the name hatherlite were also collected on Leeuwfontein [320]. As was stated by Molengraaff,[3] the name hatherlite is not applicable because the old powder factory "Eerste fabrieken" or "Hatherley factory" is situated to the south of the Magaliesberg Range and has nothing to do with the factory on Leeuwfontein [320].

[1] G. A. F. Molengraaff, "Note on Our Present Knowledge of the Occurrence of Nepheline Syenite in the Transvaal," *Trans. Geol. Soc. South Africa*, VI (1903), p. 89.

[2] J. A. L. Henderson, *On Certain Transvaal Norites, Gabbros, and Pyroxenites and Other South-African Rocks*, London, 1898.

[3] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 46.

In the *Annual Report of the Geological Survey of the Transvaal* for 1903, A. L. Hall[1] gives an account of the rocks from Leeuwfontein [320] and Zeekoegat [287] which is followed by a petrographical description of these rocks and those on Walmansdal [116] and the newly discovered occurrence on Franspoort [426].

On Leeuwkrall [396], about 5 km. to the northwest of Hamanskraal station, H. Kynaston[2] discovered two occurrences of syenitic rocks, the southern one locally graduating into nepheline syenite. It is a porphyritic foyaite similar to some of the dike rocks which occur to the southeast of the Pilandsberg. On Rietfontein [451] and Spitskop [463] an interesting occurrence of nepheline syenites within the red granites was discovered by Hall[3] in 1910; and Wagner[4] mentions the occurrence of a dike of basic camptonite cutting through the Waterberg sandstones on Buffelspruit [1920], which means probably that nepheline syenites occur at a deeper level.

The intrusion on Leeuwfontein [320].—To the east of Pretoria, near Franspoort [426], the ridges of quartzite belonging to the Pretoria series bend to the southeast; the Magaliesberg quartzites have been extended in length, while the Daspoort and Timeball quartzites were strongly pressed in a direction slightly oblique to the strike of the strata.

In describing the dislocations connected with the intrusion of the igneous complex of the Bushveld, Molengraaff[5] supposed that at those places where the circumference of the complex shows a convex curve interesting phenomena may be expected. We saw that the Pilandsberg intrusion is located where the Pretoria series,

[1] A. L. Hall, "On the Area to the North of the Magaliesberg Range and to the East of the Pietersburg Railway Line," *Annual Report of the Geol. Survey of the Transvaal*, 1903, p. 38.

[2] H. Kynaston, "On the Area Lying North-West of Pretoria, between the Magaliesberg Range and the Salt Pan," *Annual Report of the Geol. Survey of the Transvaal*, 1905, p. 29.

[3] *Annual Report of the Geol. Survey of the Transvaal*, 1910.

[4] P. A. Wagner, "Note on an Interesting Dyke Intrusion in the Upper Waterberg System," *Trans. Geol. Soc. South Africa*, 1912.

[5] G. A. F. Molengraaff, *Proc. Geol. Soc. of South Africa*, 1905; "Criticism on Messrs. A. L. Hall and F. A. Steart: On Folding and Faulting in the Pretoria Series," *Trans. Geol. Soc. South Africa*, VIII (1905), 7–15.

which from Rustenburg strike in a northeasterly direction, bend again to the west, and the nepheline syenite intrusions to the northeast of Pretoria are found where the ridges of quartzite bend to the southeast. The foyaite intrusion on Franspoort [426] is entirely surrounded by Magaliesberg quartzite and is clearly intrusive in them. Near the intrusion on Leeuwfontein [320], which borders "felsites" only on the north, the Magaliesberg quartzites cover a large surface in consequence of numerous faults. Following the valley of the Pienaars River to the north, we see a succession of red "felsites" with an approximate east-west strike and a varying dip to the north, alternating with eruptive breccias, conglomerates, and basic effusive and dike rocks. More to the north, on Roodeplaat [314], they are covered by shales and syenitic rocks of doubtful age, and on Paarderfontein [338], at a great distance from the foyaite, dikes of tinguaitic and andesitic character, which in part are connected with the intrusion on Leeuwfontein [329], cut through the sandstones and conglomerates of the Waterberg system. The chemical composition of a tinguaite of Paardenfontein [338] closely agrees with that of the normal foyaites on Leeuwfontein [320]. The small differences are similar to those which characterize the nepheline syenites and accompanying tinguaite dikes from other regions.

An interesting dike of basic camptonite has recently been described by Wagner.[1] It occurs on Buffelspruit [1920] in the Waterberg district and cuts through Waterberg sandstone. This proves again that the intrusion of nepheline syenite with which the dike most probably is connected is younger than the Waterberg sandstones.

The "felsites" are the effusive equivalents of the intrusive rocks on Leeuwfontein [320]. The liebenerite porphyries, which in the southern part of Roodeplaat are exposed over a long distance in the valley of the Pienaars River, show the same characteristics as the liebenerite porphyries of Alnö and the Tyrol. But also the dense weathered rocks of which the mineralogical composition could not be recognized under the microscope belong to the alkali

[1] P. A. Wagner, "Note on an Interesting Dyke Intrusion in the Upper Waterberg System," *Trans. Geol. Soc. South Africa*, 1912.

rocks, as was proved by chemical tests. After treating the powder with hydrofluoric acid, only 0.4 of its weight was evaporated, and a simple calculation makes evident that the Al partly occurs in feldspars, partly in feldspathoids. Microchemically the residue gave a strong soda reaction and a very feeble potash reaction. From this it is evident that "felsites" which are the effusive equivalents of the intrusive rocks are genetically connected with the alkali rocks of the intrusion on Leeuwfontein [320].

An exact petrographical examination will greatly assist in the determination of the stratigraphical place of the different "felsites." Identity in age for the felsophyres of the Waterberg district and of the phonolites of Leeuwfontein [320] would seem to be in the highest degree improbable.

From a petrographical point of view there is much resemblance between the rocks of Leeuwfontein [320] and those of the Pilandsberg; the association of foyaites of varying composition with red syenites and effusive rocks is a common characteristic. The rocks on Leeuwfontein [320] near the old dynamite factory are principally red syenites and red hololeucocratic feldspar rocks; in the southern part the *leeuwfonteinites* with accompanying porphyritic equivalents occur. The porphyritic rocks sometimes form well-defined dikes.[1] Leeuwfonteinite porphyry and monzonite porphyries are found between Leeuwfontein [320] and Franspoort [426] and along the path to Derde Poort [469]. The numerous varieties of foyaite occur near the boundary of the farms Leeuwfontein [320] and Zeekoegat [287]; they will be described in detail in a forthcoming petrographical paper. The normal foyaite of this region is a coarse-grained, leucocratic, aegirine-amphibole foyaite. In varieties rich in feldspathoids (particularly sodalite) aegirine is the only dark constituent; they pass into rocks which are nearly free from feldspar (*tawites*). Rocks very rich in titanite (*pienaarites*) occur at several places. The rocks on Leeuwfontein [320] differ from those of the Pilandsberg by the absence of rare minerals in the latter rocks. In other nepheline-syenite regions the rare minerals are

[1] The leeuwfonteinites are the same rocks as Henderson's hatherlites (anorthoclase syenites), cf. Henderson, *On Certain Transvaal Norites, Gabbros, and Pyroxenites and Other South-African Rocks.* They contain much plagioclase and their composition varies between that of the alkali monzonites and that of the alkali syenites.

also often limited to the aegirine foyaites and the arfvedsonite foyaites and are wanting in the foyaites with barkevikitic amphibole. The rare minerals and a not very small quantity of lime in the magma seem to exclude one another (compare the analysis of the normal foyaite of Leeuwfontein, which has been given in my previous paper). The association of foyaites with leeuwfonteinites which besides barkevikite also contain plagioclase makes it probable that the CaO content of the common mother-magma was rather considerable.

The rocks of the neighborhood of Leeuwfontein [320], which hitherto have been studied under the microscope, belong to the following groups:

1. Aegirine foyaites
   Leucocratic rocks
   Pienaarites (melanocratic rocks rich in titanite)
2. Aegirine-amphibole foyaites
3. Tawites
4. Feldspar rocks
5. Aegirine-foyaite porphyries
6. Aegirine-amphibole foyaite porphyries
7. Leeuwfonteinites
8. Leeuwfonteinite porphyry and monzonite porphyry
9. Tinguaite porphyries
10. Monchiquites
11. Augitites
12. Andesitic camptonites
13. Doleritic nepheline basalts
14. Diabases
15. Liebenerite porphyries
16. Bostonites
17. Phonolites

H. Kynaston[1] mentions that *the foyaite of Walmansdal* [116] is clearly intrusive in the "felsites."

Nepheline syenite region to the west of Lydenburg.[2]—This region covers a surface which has about the same extension as that on Leeuwfontein [320]. It is surrounded by red granites and occurs

[1] H. Kynaston, "The Geology of the Country Surrounding Pretoria," Explanation Sheet I, *Geol. Surv. of the Transvaal*, 1907, p. 28.

[2] A. L. Hall, in *Annual Report Geol. Surv. of the Transvaal*, 1910.

close behind the zone of ultra-acid rocks which Hall discovered at the boundary between the granites and the basic margin of the igneous complex of the Bushveld. The specimens which Mr. Hall kindly put at my disposal during my stay in the Transvaal are melanocratic lujaurites and lujaurite porphyries, which sometimes show a schistose structure. The colorless minerals are sometimes very subordinate and microscopically the rocks seem to consist almost wholly of fine needle-shaped crystals of aegirine. These very melanocratic lujaurites were rare in the Pilandsberg complex, but seem to cover the greater part of this newly discovered occurrence.

Foyaites also occur, and it is interesting to find the association of lujaurites with leucocratic feldspathoid rocks (*urtites*), which consist chiefly of nepheline. The association of lujaurites and urtites in the peninsula of Kola (they received their names from the same place—Lujavr Urt) is also a characteristic of this district.

An isolated mass of strongly metamorphic limestone is inclosed within the alkali rocks.

ORIGIN AND AGE OF THE NEPHELINE SYENITES AND ALLIED ROCKS

It does not seem improbable that the nepheline syenites have originated from the same sources as the granites and norites of the Bushveld. The formation of the basic margin in the main intrusion of the Bushveld proves that magmatic differentiation took place on a very large scale. Toward the periphery the rocks become more and more basic, while granites occupy the central portion. When tested in detail, the view of general increase of basicity from the center toward the periphery requires modification. Hall[1] has described a zone of ultra-acid rocks with 97 per cent SiO_2 in the red granites close to the boundary with the norites to the west of Lydenburg. He considers these rocks as a product of extreme differentiation, which could take place near the basic margin, when the viscosity of the granitic magma was already strongly increased. That sometimes the acid and basic rocks pass gradually into one another possibly depends on the depth to which the complex has been exposed by erosion.

[1] A. L. Hall, "Note on Certain Widespread Ultra-Acid Rocks Occurring along the Margin of the Bushveld Granite, etc.," *Trans. Geol. Soc. South Africa*, XIII (1910), p. 10.

If ultra-acid rocks have differentiated from the granitic magma, the residual magma will be enriched in Al_2O_3, and alkalies with regard to SiO_2 and its composition will more or less agree with that of the nepheline syenites. This kind of differentiation may have taken place on a much larger scale at a greater depth, which has not been exposed by denudation. It is interesting to find an occurrence of nepheline syenites on Rietfontein [451] and Spitskop [463], close behind the zone of ultra-acid rocks.

The coarse textures, the rather indefinite order of crystallization, the numerous poikilitic structures,[1] the abundance of fluorine and rare minerals with a highly complex constitution, which are characteristic for many of the nepheline syenites in the Transvaal, make it probable that these rocks crystallized from a residual magma in which the volatile constituents were concentrated and which may have crystallized at rather low temperatures. Some of the nepheline syenites are certainly younger and may be considerably younger than the sandstones and conglomerates of the Waterberg system; the time at which the different intrusions have risen to the present level and the time at which they have consolidated may have varied between wide limits.

The age of an intrusive rock is determined by the time of its consolidation, and it is very probable that the alkali magmas remained fluid during a very long period of igneous activity. When these magmas which are rich in volatile substances shall crystallize will greatly depend upon the eventual loss of these substances, which may have been the immediate cause of crystallization quite as much as of any actual cooling.[2]

Only some characteristic features of the various igneous rocks have been dealt with; as has been stated above, it does not seem improbable that the nepheline syenites and allied rocks have originated from the same sources as the granites and the norites of the Bushveld. To the petrologist there are many very interesting problems with regard to the origin and age of the different rock types which would repay further research.

[1] H. A. Brouwer, "On Peculiar Sieve Structures in Igneous Rocks Rich in Alkalies," *Proc. Kon. Akad. Amsterdam*, November, 1911.

[2] A. Harker, *The Natural History of Igneous Rocks*, 1909, p. 186.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Flett, J. S., and Hill, J. B. *The Geology of the Lizard and Meneage.* Mem. Geol. Surv., Sheet 359. London, 1912. Pp. 280, pls. 15, figs. 10, bibliography 10 pp.

The rocks of the Lizard, probably of Archean age, represent an igneous complex of serpentine, gabbro, and gneiss, surrounded by an aureole of hornblende-schists and metamorphosed sedimentary rocks—mica-schists, green-schists, and quartz-granulites. The hornblende-schists were originally basic igneous rocks, but they are now so much altered that their original character as extrusive, tuff, or intrusive cannot be determined in every case. Some of them contain sedimentary material and possibly represent volcanic ashes. The time that elapsed between the formation of the schists and the intrusion of the serpentine is not known, but most of the rocks of the aureole probably were already in a metamorphosed condition at the time of the intrusion of the basic rock. Besides the serpentine there is also a coarse hornblende-schist in some places, which may represent dolerite sills intruded immediately before the basic rock.

Numerous chemical analyses and photogravures of thin sections make the memoir a valuable work for reference. It is a notable contribution to the literature of serpentine.

Flett, J. S. "The Geology of the Lizard," *Proc. Geologists' Assoc.*, XXIV (1913), 118–33, pls. 3, map 1.

A brief summary of the preceding paper on the geology of the Lizard, intended for the use of members of the Geologists' Association on their Easter excursion, 1913.

Flett, J. S., and Hill, J. B. "Report of an Excursion to the Lizard, Cornwall," *Proc. Geologists' Assoc.*, XXIV (1913), 313–27, pls. 4.

Foye, Wilbur G. "Nephelite-Syenites of Haliburton County, Ontario," *Amer. Jour. Sci.*, XL (1915), 413–36, figs. 9.

The nephelite-syenite laccoliths of Haliburton County, central Ontario, are described together with the associated rocks. A number

of analyses with recomputations in the C.I.P.W. system are given. Among the rocks are syenite, canadite, nephelite-pegmatite, various contact rocks, hornblende-nephelite rock, monmouthite, biotite-nephelite rock, and pegmatitic nephelite-syenite. The writer thinks that the close association of the granite-pegmatite with the nephelite-syenite indicates that they originated from a primary granite magma at about the same time. Following Daly, he thinks that the nephelite-syenites were produced by the action of limestone on the granite magma.

GOLDMAN, MARCUS I. "Petrographic Evidence on the Origin of the Catahoula Sandstone of Texas," *Amer. Jour. Sci.*, XXXIX (1915), 261–87, figs. 12.

Thinks the Catahoula sandstone originated from wind-blown sand in an arid region. The arrangement of fossils indicates subaërial burial in blown sand in some cases, and burial by wind, but in a quiet body of water, in others. Evidence for the interpretation of disintegrated sediments in general is considered in detail.

KATO, TAKEO. "Mineralization in the Contact Metamorphic Ore Deposits of the Ofuku Mine, Prov. Nagato, Japan," *Jour. Geol. Soc. Tokyo*, XX (1913), 13–32, pl. 2, figs. 3.

The copper ores of the Ofuku mine are contact metamorphic deposits in sedimentary rocks at a short distance from an igneous body. They are accompanied by typical contact minerals, such as wollastonite, garnet, vesuvianite, etc., which were deposited metasomatically from solutions derived from the igneous magma. The character of the solutions changed gradually during the period of metamorphism. At first they were very siliceous; later they became more basic, and rich in iron and silica and with more or less sulphide ores, and finally very basic and rich in copper and iron sulphide and poor in silica.

KOTO, B. "On the Volcanoes of Japan," *Jour. Geol. Soc. Tokyo*, XXIII (1916), 1–13, 17–28, 29–55, to be continued.

These three papers represent the beginning of a series of articles by Doctor Koto on the Japanese volcanoes. Of the 170 post-Tertiary volcanoes of Japan, 55 are active. All the recent lava is andesitic, but some of the earlier flows were plagioliparite and basalt. The writer describes each volcano in brief form, classifying the cones according to the system proposed by Schneider, and gives references to previous work.

KOZU, S. "Petrological Notes on the Igneous Rocks of the Oki Islands," *Science Repts. Tokoku Imp. Univ., Sendai, Japan.* Second Series, Vol. I (1913), No. 3, 25–56, pls. 4, figs. 5.

The Oki Islands lie about 65 kilometers off the coast of Honshu, on the Korean side. They consist mainly of volcanic rocks extruded between the middle of the Tertiary and the beginning of the Pleistocene, and lie upon or were intruded into the Tertiary beds which form the base of the islands. The succession of the igneous rocks cannot be exactly determined in all cases but it appears to be as follows, beginning with the most recent:

10. Holocene sediment, a river deposit of limited extent in valleys
9. Trachydolerites and basalts
8. Pleistocene (?) deposits
7. Trachytic rocks
6. Trachydolerites
5. Banded alkalic rhyolites
4. Alkalic rhyolites
3. Quartz-syenites and schistose granitic rocks
2. Andesites
1. Tertiary deposits

The various rock-types are described in detail, chemical analyses are given for most of them, and the names in the C.I.P.W. system are determined.

Reviews

Physiography of the Beaverdell Map-Area and the Southern Part of the Interior Plateaus of British Columbia. By Leopold Reinecke. Geol. Surv., Canada, Museum Bull. No. 11, 1915. Pp. 58, pls. 5, figs. 3, map 1.

A study of the Beaverdell area is of value because its history is characteristic of the whole plateau region of British Columbia. Following the eruption of lavas (Nipple Mt. series) in early Miocene a mature topography was developed. Late in the Tertiary the canyon-cutting stage was inaugurated by an uplift of about 1,000 feet. Pliestocene glaciation, first by continental ice from the north and later by valley glaciers, modified the youthful topography. The present areal ratio of uplands to valleys is three to one.

H. R. B.

Report on the Copper Deposits of the Eastern Townships of the Province of Quebec. By J. Austen Bancroft. Dept. of Colonization, Mines and Fisheries, Mines Branch, 1915. Pp. 295, pls. 10, figs. 9, map 1.

Lenticular bodies of pyrite carrying a little chalcopyrite occur in highly metamorphosed igneous and sedimentary rocks. A large proportion of the deposits have been formed by irregular impregnation and replacement along shear zones within altered igneous rocks. Other deposits occur at the contacts of the intrusives and as impregnations or partial replacements of limestones. The schistose intrusives seem to have been the source of the sulphide ores.

Development in this region was begun during the Civil War, when the price of copper was abnormally high. Since 1869 only a few companies have operated. Four properties have yielded large profits; no others have repaid the money spent upon them. The future development of the mines depends largely on the utilization of the sulphur content of the ores in the manufacture of sulphuric acid, or other chemicals.

H. R. B.

Notes on the Geology and Paleontology of the Lower Saskatchewan River Valley. By E. M. KINDLE. Geol. Sur., Canada, Museum Bull. No. 21, 1915. Pp. 25, pls. 4.

Description of Silurian sections and faunas, including new species, *Leptaena sinuosus* and *L. Parvula.*

H. R. B.

The Geology and Mineral Resources of the Buller-Mokihinui Subdivision, Westport Division, New Zealand. By P. C. MORGAN and J. A. BARTRUM. New Zealand Dept. of Mines, Geol. Surv., Bull. No. 17, new series, 1915. Pp. 210, pls. 19, figs. 1, maps 9.

This area is situated on the northeast coast of the South Island of New Zealand. The rocks are described as consisting of the Aorere series of metamorphosed Siluro-Ordovician sediments intruded by pre-Triassic granites, a coal-bearing Eocene series, the Oamaru series of Miocene age, and Quaternary deposits, both Pleistocene and Recent.

The Westport district is famous for its gold placers, fluvial and marine gravels having yielded a total of £4,675,000. The industry has greatly declined in recent years. The Eocene coal is a high-grade bituminous variety. The total tonnage is estimated at 123,000,000 tons, of which 60,000,000 is extractable. The Miocene series contains considerable quantities of brown and lignitic coal.

H. R. B.

The Squantum Tillite. By ROBERT W. SAYLES. Bull. Mus. Comp. Anat., Harvard College, LVI, No. 2 (1914), 141–75, pls. 12.

For many years the origin of the Roxbury conglomerate has been a subject of debate. As early as 1875 W. W. Dodge stated his belief in the glacial origin of these beds; the writer has at last established this view. The Roxbury series, comprising the Roxbury conglomerate, the Squantum tillite, and the Cambridge slate, is of late Paleozoic age, probably Permian. If there is no duplication of beds by folding, the tillite is 600 feet thick. It is an unstratified mass of unassorted materials much affected by dynamic movements, with the development of secondary cleavage. The rock fragments are of several kinds, variable in size, and mostly angular or subangular in shape. Striated stones were found at four localities.

The character of the included rock fragments suggests that the ice moved from the southeast. Intercalated slate beds indicate recessions of the ice. Whether they represent temporary retreats or long interglacial epochs is not known. Two conglomeratic beds below the principal tillite are of probable glacial origin, though it is not certain that they were deposited directly by the ice. H. R. B.

Geology of the Lake Pleasant Quadrangle, Hamilton Co., N.Y. By William J. Miller. New York State Museum, Bull. No. 182, 1916. Pp. 75, pls. 10, figs. 4, map 1.

The Lake Pleasant Quadrangle lies in the south central Adirondacks. The Grenville series of meta-sediments and intrusives outcrops over most of the region and is cut by a network of normal faults. Two small areas of Paleozoic strata are preserved by the dropping of fault blocks. The maximum thickness of this section is 500 feet. The formations preserved are: Potsdam sandstone, Theresa beds, Little Falls dolomite, Black River (Lowville) limestone, Trenton limestone, and Canajoharie (Trenton) shale.

The normal syenites of the region grade into basic syenites, also into granitic syenites and granites. The basic phases are attributed to the assimilation of dark Grenville gneisses. Pure differentiation has been the principal factor in the production of the silicic phases. Transitions from gabbro into basic syenite are described as due to assimilation by the gabbro. H. R. B.

Geology and Underground Waters of the Northern Llano Estacado. By Charles L. Baker. Bull. Univ. Texas, No. 57, 1915. Pp. 225, pls. 10, maps 3.

For half a century or more the Llano Estacado has been famous for its stock-raising. Recently there has been a serious attempt to utilize the ground water for purposes of irrigation. The supply of shallow water is found to be insufficient to irrigate all the land that it underlies. Conservation is therefore of first importance, but unless dry farming proves more successful than in the past this region will always be chiefly a stockman's country.

Previous geologic work is largely confirmed by the present study. The strata represented are the Permian red-beds, the Upper Triassic Dockum group, comprising the Tecovas and Trujillo formations, marine beds of upper Comanchean age, possibly some Cretaceous rocks, and imperfectly known Miocene and later Cenozoics. H. R. B.

Petroleum and Natural Gas in Oklahoma. By C. W. SHANNON and L. E. TROUT. Okla. Geol. Surv., Bull. No. 19, Part I, 1915. Pp. 133, pls. 7, figs. 4.

The great public demand for information concerning oil and gas necessitates the publication, not only of detailed reports on individual fields, but also of papers containing general information regarding the oil and gas business. The present bulletin is designed to meet both demands. It is published in two parts. Part I deals with the general phases of the industry, and includes a short discussion of the geology of Oklahoma. Part II gives a more detailed account by counties of the oil and gas fields of the state.

H. R. B.

The Willow Creek District, Alaska. By S. R. CAPPS. U.S. Geol. Surv., Bull. No. 607, 1915. Pp. 86, pls. 15, figs. 5.

An area of 90 square miles at the head of the Little Susitna River, which enters Cook Inlet from the north, is described. The geologic formations are pre-Jurassic mica schists cut by quartzdiorites, and an Eocene sedimentary series with interbedded basaltic lava flows. Alaskite dikes and gabbro masses occur in association with the larger intrusives. Gold occurs in placers and quartz lodes. The latter are quartz-filled fissures in the quartz-diorite carrying free gold and sulphides.

H. R. B.

The Broad Pass Region, Alaska. By FRED A. MOFFIT. U.S. Geol. Surv., Bull. No. 608, 1915. Pp. 80, pls. 8, figs. 3.

The Broad Pass region comprises an area of about 3,700 square miles along and south of the axis of the Alaska Range east of Mount McKinley. The oldest rocks are of Devonian age, representing the same general horizon as the Devonian of the Mount McKinley and Porcupine River regions. The Mesozoics are less deformed than the Devonian series. Basic lava flows are apparently overlain by upper Triassic slates which are probably equivalent to the "undifferentiated Paleozoic" series of slates and graywackes along the south flank of the Alaska Range, as described by Brooks, Capps, and Eldridge. A series of slate, graywacke, and conglomerate is provisionally assigned to the Jurassic. At some time before the Tertiary these rocks were folded and intruded by igneous masses. The Eocene is represented by the Cantwell formation, in places intensely folded and cut by granites and diorites. The sections on Quaternary deposits, igneous rocks, and glaciation are by Joseph E. Pogue.

H. R. B.

Geology and Oil Resources of the West Border of the San Joaquin Valley North of Coalinga, California. By ROBERT ANDERSON and ROBERT W. PACK. U.S. Geol. Surv., Bull. No. 603, 1915. Pp. 220, pls. 14, figs. 5.

The region described in this bulletin is a strip 8 to 20 miles wide and 130 miles long lying along the east flank of the Diablo Range and the adjacent western edge of the San Joaquin plain. This foothill belt was studied with a view to determining whether or not oil fields exist, as in the Coalinga and other districts farther south. In so far as finding new oil fields is concerned, the examination proved disappointing. Organic shales were found in great quantity, but there are few spur folds running out toward the valley. The presence of oil pools to the south is determined by such folds.

The oldest rocks in the Diablo Range belong to the Franciscan formation, of supposed Jurassic age, which is separated from the oldest Cretaceous rocks by a great unconformity. The Knoxville group (Comanche) is believed to be absent. The Chico (Cretaceous) is represented by the Panoche and Moreno formations, marine shales and sandstones that reach the enormous thickness of 24,000 feet. The Moreno, composed largely of organic remains such as diatoms and foraminifers, has been referred by some authors to the Tertiary, but it is now found to contain Cretaceous fossils. Hitherto strata of this type have been known in California only in the Tertiary.

The Martinez (lower Eocene) is present only in the southern part of the area, where it is represented by 5,000 feet of marine beds. The Tejon (upper Eocene) is present throughout the region, varying in thickness from 50 to 2,200 feet. The Oligocene is represented by the Kreyenhagen diatomaceous shale, with unconformities above and below. In the southern part of this belt the Miocene is represented, as in the Coalinga district, by the Vaqueros, Santa Margarita, and Etchegoin-Jacolitos formations, with a maximum thickness of 5,000 feet, each separated from the next adjoining by an unconformity. The Big Blue serpentine, formerly considered to represent the lower part of the Santa Margarita, contains typical Vaqueros fossils. Farther north the lower and middle Miocene were not differentiated. The San Pablo is equivalent in part at least to the Etchegoin-Jacolitos. Post-Miocene beds up to 2,200 feet thick are tentatively correlated with the Tulare formation.

The local factors influencing the accumulation of oil, evidences of oil in the region, and the future possibilities of development are dis-

cussed in detail. The oil is believed to have been derived from the two organic shales, and apparently each gave rise to a different type of oil—the Moreno to a light paraffin oil and the Kreyenhagen to a heavy asphalt oil. The diatoms are believed to have been the greatest contributors in the formation of the oil.

H. R. B.

Mineral Resources of Alaska for 1914. By ALFRED H. BROOKS and Others. U.S. Geol. Surv., Bull. No. 622, 1915. Pp. 380, pls. 11, figs. 8.

This volume is the eleventh of a series of annual bulletins summarizing the results of the investigations of Alaskan mineral resources and the status of the industry in the territory. Fourteen papers deal with the mineral resources of certain districts.

The gold and copper deposits of the Port Valdez district are descibed by B. L. Johnson. The country rock includes basic lavas, slates, graywackes, and other sediments of Mesozoic age. Gold occurs in quartz-filled fissure veins formed at moderate depths; the copper chiefly as sulphide impregnations and replacements of sheared zones along the fractures. The mineral association in both gold and silver ores is practically the same, varying only in relative proportions. The sulphide minerals are pyrite, chalcopyrite, galena, sphalerite, and some pyrrhotite and arsenopyrite. There was but one period of mineralization. As in the Ellamar district, both types had a common origin in solutions that circulated subsequent to late Mesozoic intrusions, with which they were probably genetically related.

P. S. Smith and A. G. Maddren describe the quicksilver prospects of the Kuskokwin region. The ore occurs in brecciated zones in Cretaceous sandstones and shales at the contacts of granitic and andesite dikes. Cinnabar, generally with stibnite, occurs in quartz veinlets and stringers. In places calcite and siderite are present. Some cinnabar has also been obtained from placer gravels, and detritus in a stream near one of the deposits contains native mercury.

H. R. B.

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—WILLIAMS, M. Y. An Eurypterid Horizon in the Niagara Formation of Ontario. [Canada Department of Mines, Museum Bulletin No. 20, No. 1574, Geological Survey, Geological Series, No. 29. Ottawa, October 8, 1915.]

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—WILLISTON, S. W. (1) The Osteology of Some American Permian Vertebrates. II. (2) Synopsis of the American Permo-Carboniferous Tetrapoda. Contributions from Walker Museum, Vol. I, No. 9. [Chicago: The University of Chicago Press, 1916.]

—WOOD, HARRY O. Effects in Mokuaweoweo of the Eruption of 1914. [American Journal of Science, 4th Series, Vol. XLI, No. 245, May, 1916.]

—WOODWARD, H. P. The Reputed Petroliferous Area of the Warren River District (Southwest Division). With a Contribution on Asphaltum from the Southern Coast of Australia, by E. S. SIMPSON, and a Petrological Contribution by R. A. FARQUHARSON. [Geological Survey of Western Australia, Bulletin 65. Perth, 1915.]

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